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The report is proposed to serve as an introduction to the theory of the Laser Exhaust Measurement (LEM) program, a detailed description of the operating characteristics of the equipment, and as a general operating manual for the entire LEM system. The LEM apparatus is composed of a number of subsystems and individual components constructed by a variety of manufacturers. The original operating manuals are included in the appendices. The eight chapters of the report present the following information: a brief description of the construction and operation of each LEM subsection and/or component; a detailed description of each of the major components; a detailed step-by-step LEM operation manual; details of xenon laser operation and adjustment; and a description of the necessary steps involved in the initial LEM assembly.

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1.0 INTRODUCTION

The Final Report of the Laser Exhaust Measurement (LEM) program is intended to serve as an introduction to the theory of LEM system operation, a detailed description of the operating characteristics of the equipment, and as a general operating manual for the entire LEM system. The LEM apparatus is composed of a number of subsystems and individual components constructed by a variety of manufacturers. The original operating manuals, warranties, etc., associated with each LEM subsystem or co. ponent are included as detached appendices of this Report for detailed reference and possible trouble-shooting purposes.

The construction and operation of each LEM subsystem and/or component is briefly described in the sections below, and the proper operating procedures are clearly detailed to prevent malfunctions or possible damage to the LEM apparatus. Certain minimal risks to operating personnel are present in the LEM equipment, and hazardous locations and/or poor operational procedures are both labeled and described in the text below. These risks are principally associated with the relatively high-pressure cooling water for the magnet, the moderately high laser excitation voltage, and the large magnetic fields present near the ends of the magnet solenoid. In each case, care has been taken to reduce or eliminate potential dangers from the LEM equipment.

A complete theoretical description of noble gas laser operation is not included here since excellent treatments are available in the literature (1--4), and only a cursory analysis of LEM operation will be presented. The Final Report is divided into two major sections: Chapters 2 through 5 comprise a detailed description of each of the major components of the LEM system, Chapter 6 contains a detailed, step-by-step LEM Operation Manual, Chapter 7 covers the details of xenon laser operation and adjustment, and Chapter 8 describes the necessary steps involved in the initial LEM assembly at the EPA.

2.0 LEM SYSTEM DESCRIPTION

2.1 Introduction

The Laser Exhaust Measurement (LEM) apparatus utilizes a Zeeman-split, neutral xenon laser capable of oscillation at a variety of wavelengths in the middle infrared. The xenon laser was initially designed to oscillate principally at 3.508 and 3.679 microns. Both of these xenon laser lines are relatively near spectral components of formaldehyde absorption bands (5). The spectral details of the formaldehyde absorption bands were not known at the beginning of the LEM program, and thus an unusually large five kiloGauss solenoid was incorporated into the LEM system design at an early stage in order to insure adequate splitting of the xenon laser line(s). The Zeeman splitting of the σ components of the $5d(7/2)^{o}_{3}$--$6p(5/2)_{2}$ transition in xenon (corresponding to the 3.508 micron laser line) is quite complex, but in general, a splitting of some 2 MHz/Gauss was expected from theoretical considerations. The magnitude of the Zeeman splitting at maximum magnetic flux was measured directly using a 3/4 meter Czery-Turner spectrometer. In addition, spectral measurements were also made at relatively small magnetic fields (several hundred Gauss) using homodyne detection in conjunction with a microwave spectrum analyzer. A maximum splitting of 1.7×10^{10} Hz (7 Å) of the 3.508 micron xenon laser line was measured with an axial magnetic field of 5500 Gauss.

In operation, the axial magnetic field is increased until the spectral splitting of the two oppositely-directed circularly polarized laser beams is sufficient to permit the observation of differential absorption (due to the presence of HCHO in the sample cell) between the two Zeeman components. For greater spectral splittings, the corresponding differential absorption should be proportionally greater.

In order to achieve relatively equal laser intensities for the oppositely-directed circularly polarized Zeeman components, ν_{+} and

ν_-, it is necessary either to

1. mechanically tune the longitudinal modes in the laser cavity so that the cavity Q is approximately the same for both ν_+ and ν_-, or
2. adjust the angular orientation of the Brewster-angle polarization compensation plate to equalize the relative intensities of the two circularly-polarized waves.

In the case of relatively low laser amplifier optical gain, it may be necessary to perform both of the above operations.

2.2 Description of LEM Operation

2.2.1 Xenon Laser

The LEM xenon laser is capable of stable CW laser oscillation at 11 wavelengths in the middle infrared (see Table 2-1, below). The relative strengths of these laser lines can be dramatically affected by varying the xenon pressure, laser discharge current, output mirror reflectivity, and laser cavity mirror separation. To permit the laboratory-grade LEM xenon laser to possess the necessary flexibility to fulfill all the necessary optimum conditions for most of these 11 laser lines, the following laser subsystems are furnished:

1. A cryogenic pressure-control system with built-in "fail-safe" features.
2. A variable dc excitation power supply.
3. A piezoelectric mirror translator assembly together with its associated electronics.
4. A thermally-compensated laser cavity with quartz rod mirror separators.
5. Easily interchangeable laser cavity output mirror assemblies.

Details regarding the optimum operating conditions for each laser line are given below in the general operating instructions for the LEM apparatus (see Section 7.2).

The xenon laser discharge tube itself is terminated with

TABLE 2-1

CW Xenon Laser Lines Obtainable with LEM Apparatus

#	Wavelength (Vacuum), Microns	Transition	Optimum Pressure	Observed Strength	Theoretical Strength (15)
1	3.108	$5d(5/2)^{o}_{3}$---$6p(3/2)_{2}$	Low to Moderate	0.1*	2.94
2	3.275	$5d(3/2)^{o}_{2}$---$6p(1/2)_{1}$	Low to Moderate	6.0	1.25
3	3.368	$5d(5/2)^{o}_{2}$---$6p(3/2)_{1}$	Low to Moderate	5.0	1.89
4	3.508	$5d(7/2)^{o}_{3}$---$6p(5/2)_{2}$	Low to Moderate	10.0	4.0
5	3.622	$5d'(3/2)^{o}_{3}$---$7p(3/2)_{2}$	Low	0.4	0.0
6	3.652	$7p(1/2)_{1}$---$7s(3/2)^{o}_{2}$	Low	0.1	0.0
7	3.680	$5d(1/2)^{o}_{1}$---$6p(1/2)_{1}$	Moderate	4.0	1.0
8	3.870	$5d'(5/2)^{o}_{3}$---$6p'(3/2)_{2}$	Low	0.4	5.0
9	3.997	$5d(1/2)^{o}_{0}$---$6p(1/2)_{1}$	Low to Moderate	3.0	0.5
10	4.153	$5d'(5/2)^{o}_{2}$---$7p(3/2)_{1}$	Low to Moderate	1.0	0.0
11	5.575	$5d(7/2)^{o}_{4}$---$6p(5/2)_{3}$	Low to Moderate	0.8	5.4

* The output power of this line increases drastically if a higher reflectivity output mirror is used.

slightly canted, narrow-band "V" anti-reflection-coated sapphire windows optimized for laser oscillation at 3.5 microns. Laser oscillation at substantially different wavelengths is generally difficult owing to the relatively high optical losses introduced by these laser tube windows. In particular, argon and krypton neutral gas lasers oscillate at shorter wavelengths than xenon due to their higher energy level structures, and hence the LEM xenon laser tube is not well adapted to the use of the laser tube for CW argon and krypton laser action. With the exception of five new argon and krypton laser lines recently discovered by the author (6), there is a dearth of argon and krypton laser lines in the 3.51 micron spectral region, and hence it was decided that in order to prolong the life of the xenon laser, the original vacuum valve would be removed and the laser tube sealed off. Before the vacuum valve was removed, however, several unsuccessful attempts were made to obtain CW laser oscillation at any argon or krypton wavelengths.

The hot cathode assembly in the LEM xenon laser discharge tube is poisoned by accidental exposure to oxygen, but if the oxygen exposure occurs when the cathode is cool, the cathode can be reprocessed. Since the LEM xenon laser already has the capability of oscillation at ten infrared laser lines, the removal of the vacuum valve is not regarded as detrimental to the overall performance of the LEM laser.

In the absence of an externally-applied magnetic field (ignoring the relatively small terrestrial field), the inhomogenously-broadened xenon laser will oscillate primarily at a number of laser frequencies corresponding to discrete longitudinal modes separated in frequency by

$$\Delta\nu_c = \frac{c}{2L} \qquad (2\text{-}1)$$

where L is the optical path length between the two laser cavity mirrors and $\Delta\nu_c$ is the intracavity mode spacing frequency. The

central frequency of this group of longitudinal modes is determined by the atomic laser transition itself, which in the case of the 3.508 micron xenon laser line corresponds to $\nu_o = 8.55 \times 10^{13}$ Hz. Thus the frequency separation, $\Delta\nu_c$, of the individual laser modes is, in general, determined by the geometry of the laser cavity, whereas the frequency centroid of laser oscillation is determined by the active laser medium (in the present case, xenon) as well as the kinetics of noble gas laser excitation.

The "natural" or homogeneously-broadened linewidth of a noble gas laser transition is inversely proportional to the lifetimes of the excited energy levels, and in the case of the 3.508 micron xenon laser line, it has been determined to be approximately 2 MHz (7). The inhomogeneously-broadened character of low pressure middle infrared noble gas lasers is due to Doppler broadening caused by the thermal motion of the gas atoms (for xenon, $\Delta\nu_D = 150$ MHz). In addition, naturally-occurring xenon contains nine stable isotopes which induce an isotopic broadening (8) of the laser line-width in addition to that produced by the Doppler effect.

The number of longitudinal modes which will oscillate in a given laser cavity is approximately equal to the ratio of the inhomogeneously-broadened linewidth, $\Delta\nu_D$, to the intracavity mode spacing, $\Delta\nu_c$. In the present xenon laser design, only a few longitudinal modes will oscillate (in the absence of a magnetic field). Gas lasers can, in addition, oscillate at several discrete frequencies at or near the kth longitudinal mode frequency, $\Delta\nu_k$, due to the presence of relatively weak transverse modes associated individually with each longitudinal mode. When the axial magnetic field is applied to the laser oscillator, the resulting Zeeman splitting is not continuous (as it is in the case of spontaneous emission), but is instead discrete, corresponding to jumps in frequency equal to $\Delta\nu_c$, given above by equation (2-1). This quantized phenomenon is caused by the requirement that the laser resonator determines the precise frequencies of laser

oscillation, whereas the laser medium determines only the approximate oscillation frequency (within the spectral linewidth, $\Delta\nu_D$).

In the case of the LEM xenon laser, the cavity length, L, is approximately 127 cm, so that $\Delta\nu_c$ = 118 MHz (from equation (2-1), above), and hence the relative changes in laser oscillation frequencies tend to be quite large for magnetic fields of several hundred Gauss. As a result, it is not a simple matter to measure accurately the relative splitting of the LEM laser for small magnetic fields in the comparatively short laser cavity required for the LEM system.

If the laser cavity mode-closing length, L, is increased from the present 127 cm to something of the order of 150 meters (9), then $\Delta\nu_c$ = 1.0 MHz, and the homodyne spectrum analysis of a Zeeman-split xenon laser becomes much more precise--this technique is very useful when used with small magnetic fields ($B \approx 200$ Gauss).

2.2.2 Calibration of Xenon Laser Spectral Splitting

As noted above, a useful technique for calibrating the relative Zeeman-splitting of the two oppositely-directed circularly polarized laser beams employs a suitable "square-law" photodetector connected directly to a high-frequency electronic spectrum analyzer. When the Zeeman-split xenon laser beam is focused on a square-law detector, an electronic beat frequency can be observed with an electronic spectrum analyzer (providing it has a sufficiently high electronic frequency response) as an rf current generated by the "beating" of the two optical waves differing in frequency by

$$\Delta\nu_s \simeq \Delta\nu_M = \frac{eBg}{2\pi m} \simeq 2 \text{ MHz/Gauss} \quad (2\text{-}2)$$

where e/m is the charge to mass ratio of the electron, g is the reduced Lande g-factor, and B is the axial magnetic field in Gauss.

The splitting defined in equation (2-2), above, is subject to the additional conditon that the longitudinal modes be spaced at intervals of c/2L, and hence in the case of relatively small magnetic fields, the Zeeman splitting becomes

$$\Delta\nu_M = K\left\{\frac{c}{2L}\right\} \qquad (2\text{-}3)$$

where K is an integer. When the magnetic field is steadily increased from zero, the discrete homodyne beats observed with a high-frequency electronic spectrum analyzer permit an approximate calibration of the Zeeman-induced spectral splitting of the xenon laser. As discussed above, the homodyne technique is much more accurate for large values of the laser cavity mode-closing length, L. Direct measurements of the maximum Zeeman splitting of a xenon laser can be made using a spectrometer, but the accuracy of the technique is relatively low in the absence of ancillary optical equipment such as a Fabry-Perot interferometer.

2.2.3 Detection of Aldehyde Concentrations

Once the spectral splitting of a given xenon laser line is determined (either theoreticaly or empirically), it is then possible to use the Zeeman-tuned xenon laser as a relatively sensitive, extremely narrow-band differential absorption device. One of the two Zeeman-components is absorbed more strongly than the other by the aldehyde gas sample, and thus by comparing the ratio of the two Zeeman component intensities at a relatively rapid rate (in the present case, the comparison frequency is 24 Hz with a provision for increasing the frequency), it is possible to infer the concentration of the sample aldehyde present in the sample cell. The technique employed here first converts the oppositely-directed circularly-polarized Zeeman components into two perpendicular plane-polarized beams by passing them through a quarter-wave plate constructed of anti-reflection-coated lithium niobate. Since the laser

is designed to oscillate at a number of infrared wavelengths simultaneously, the assembly carrying the quarter-wave plate also mounts a narrow-band interference filter passing only one of the oscillating wavelengths. The two Zeeman-split laser beams then pass through a ZnS compensating plate (see Figure 2-1) to equalize the intensities of the two laser beams (if necessary). The beams then pass through the test cell containing the sample absorbing gas. After passage through the test cell, the relative intensities of the two Zeeman components will, in general, be different, and an electronic data-processing system measures the ratio of the Zeeman component intensities. The electronic data-processing system consists of an autolock amplifier, a dc reference amplifier, and a digital ratiometer. Display of the data output is provided both by a digital readout and a chart recorder.

The time variation of the optical signal detected by the photodetector is given by

$$I = I_+ \cos^2(\omega t) + I_- \sin^2(\omega t) \qquad (2\text{-}4)$$

where I_+ is the intensity of the CCW Zeeman component, I_- that of the CW Zeeman component, and ω is the angular frequency of the analyzer prism shown in Fig. 2-1. It is evident from equation (2-4) that when the relative intensities of the Zeeman components (I_+ and I_-) are equalized, the output signal from the photodetector should be entirely dc. This situation corresponds to zero differential absorption by the aldehyde sample cell. Unfortunately, any output fluctuations in the laser beam(s) due to mechanical vibrations, noise, etc., would appear as spurious noise on top of the dc signal.

When the intensities of the two Zeeman components are not equal, or when $I_+ > I_-$, then equation (2-4) can be written:

$$I = I_- + \Delta \cos^2(\omega t) \qquad (2\text{-}5)$$

where we have written

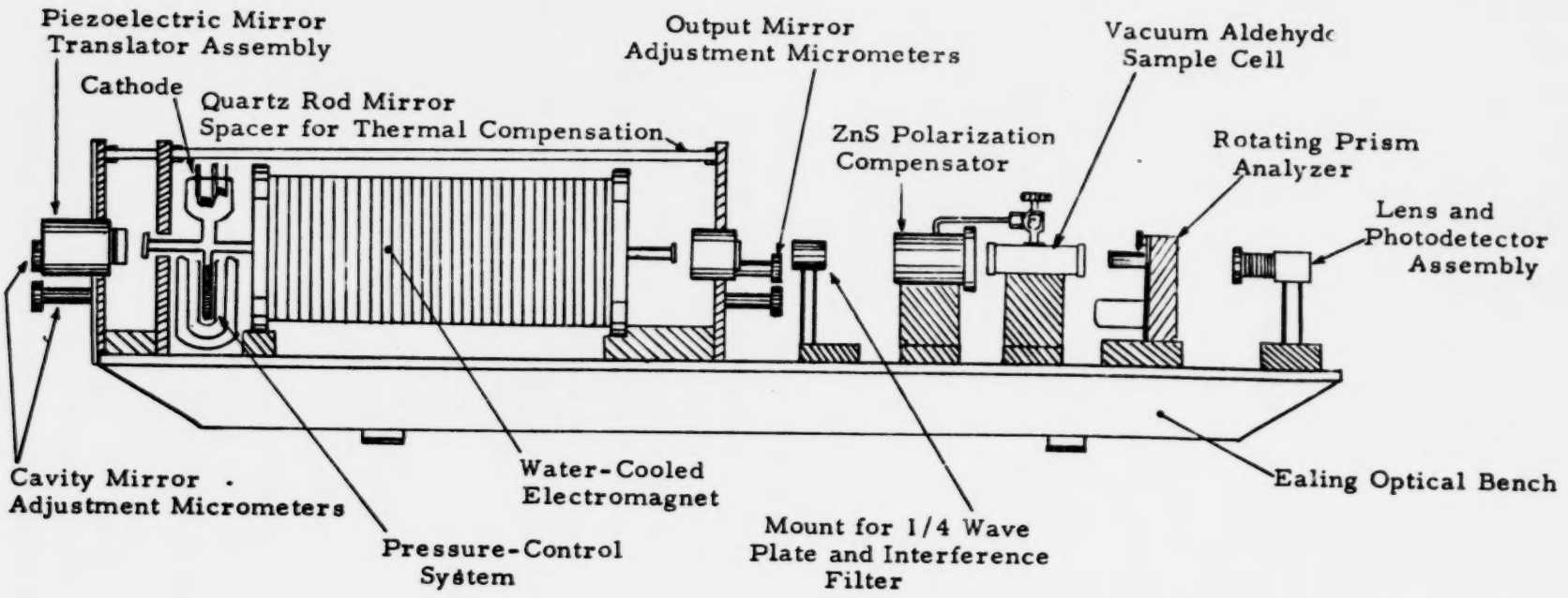

Figure 2-1 Diagram of LEM Apparatus Mounted on an Optical Bench

$$\Delta = I_+ - I_- \qquad (2\text{-}6)$$

Making the usual trigonometric substitution, equation (2-5) can be written:

$$I = I_- + \frac{\Delta}{2}(1 + \cos 2\omega t) \qquad (2\text{-}7)$$

The relative Zeeman intensities (I_+ and I_-) are not equal when a suitable absorbing gas (such as formaldehyde) is placed in the sample cell, and thus under these circumstances, the photodetector output consists of both ac (at a frequency of 2ω) and dc components. A magnetic pickup mounted on the rotating analyzer prism assembly provides phase information to the phase-sensitive detection section of the autolock amplifier.

In actual operation, some undesirable beam steering by the analyzer prism produces an ac signal at an angular frequency of ω, and it is necessary for the electronic system to ignore this spurious signal component. It is desirable to obtain a differential absorption fraction of at least one part in 10^3, and the intial tests of the electronic data-processing system indicate that several parts in 10^5 can be measured if the electrical signals input to the system are very stable. It is evident from equations (2-5) and (2-7) that the differential absorption fraction, ξ, is given by

$$\xi = \frac{\Delta}{2I_- + \Delta} \simeq \frac{\Delta}{2I_-} \qquad (2\text{-}8)$$

Thus, the differential absorption fraction, ξ, is simply the ratio of the ac photodetector signal to the dc photodetector signal.

2.2.4 Electronic System Detection Problems

A number of problems appeared during the assembly and testing phases of the LEM apparatus in the photodetection and electronic signal processing areas of the LEM system. These problems are briefly

described below.

Electronic Data-Processing System

Difficulty was initially encountered with the lock-in amplifier circuitry when it was discovered that it was not possible to obtain a frequency-lock on the reference input signal from the analyzer prism magnetic pickup. A tunnel diode wired in parallel with the magnetic pickup permitted the lock-in amplifier to match the reference frequency (2ω), but the output from the lock-in amplifier remained quite noisy. The noise was traced to three problem areas:

1. Ground loops,
2. beam steering by the analyzer prism, and
3. vibration introduced into the laser cavity by the massive magnet cooling water pump.

The latter two problems are difficult to solve, and at present they represent the limiting mechanism for achieving high sensitivity of the LEM apparatus for detecting low concentrations of aldehydes.

Photodetectors

There were three photodetectors originally considered for use on the LEM program. They were:

1. A thermoelectrically-cooled PbSe photodetector,
2. a liquid nitrogen-cooled InSb detector, and
3. an uncooled, room temperature InAs photodetector.

The PbSe photodetector proved to be too noisy for use as the LEM detector, the InSb photodetector exhibited problems with moisture condensing on the entrance window, and the InAs photodetector has a spectral sensitivity which cuts off beyond 3.5 microns. As a consequence of these various problems, the InSb detector was chosen as the prime photodetector until the Zeeman-splitting magnetic field experiments were completed. These experiments revealed that the proposed 3.68 micron laser line would not oscillate in a strong magnetic field, and hence the major objection to the use of the room-temperature InAs detector was removed. Thus, the present LEM configuration uses a InAs photodetector in the electronic data-processing system.

Analyzer Prism

The original LEM optical design included an air-spaced lithium niobate Glan-Thompson prism as the rotating polarization analyzer. Considerable fabrication difficulties were experienced by the prism vendor, and the $LiNbO_5$ prism was eventually delivered more than four months late. Since the original LEM program schedule was for only six months, total, the prism delay produced an overall delay in the LEM program.

As a consequence of the slipped schedule and a diminishing level of confidence that the vendor would ever be able to deliver a prism of adequate quality, a backup analyzer prism of another type (Rochon), material, and vendor was ordered. When both prisms were eventually received (within a week of one another), it was found that both prisms deflect the transmitted (extraordinary) ray, thereby inducing an amplitude modulation on the detected laser beam of angular frequency ω. Two solutions to this beam-steering problem were apparent:

1. Use a larger surface area detector in conjunction with a short focal-length lens to minimize the effect of the beam steering, and
2. insert a compensating wedge after the analyzer prism to correct the deflection angle.

The first approach was selected because of the time-consuming problems associated with fabricating and properly installing a suitable compensating wedge.

Background Noise Generated by Water Pump Vibration

In addition to the noise introduced by the prism beam steering, a serious background noise problem is generated by the vibrations induced by the massive thrust of the large magnet cooling water pump. The most obvious elimination of this source of noise is to eliminate the use of the cooling water pump, an attractive solution if flowing tap water is to be used to cool the magnet in any case. The Environmental Protection Agency is considering using tap water for the cooling of the magnet, at least for magnetic fields sufficiently low

that the cooling water does not boil. Another partial solution to the problem makes use of the narrow-band properties of the lock-in amplifier circuitry used in the LEM electronics. This solution involves increasing the angular velocity of the analyzer prism until its magnitude is higher than the major (semi-random) low frequencies induced by the vibration of the water pump. The analyzer mechanism has been modified to accept different gear ratios, and hence the analyzer can be set at a number of angular speeds corresponding to the requirements of the experimenter(s).

2.2.5 Xenon Laser Pressure Control System

Noble gas lasers in general exhibit a serious gas adsorption phenomenon often referred to as gas "clean-up." If, for example, a noble gas laser is filled to an optimum pressure for laser operation, gas adsorption into the laser tube walls occurs quite rapidly, and the laser oscillation will often cease after only one hour of operation. If an operating noble gas laser tube is repeatedly filled at the optimum pressure after many hours of operation, the long term pressures remain unpredictable.

The solution to this serious problem of gas "cleanup" employed for the LEM xenon laser was to grossly overfill the laser tube with xenon, and then trap cryogenically the excess gas with a tube appendage immersed in a suitable cryogen. Continuous pressure control is afforded by electrically heating the cold finger while it is immersed in a bath of liquid nitrogen at a temperature of 77°K. When operated without the cold finger heater, the xenon pressure can be controlled by either

1. Adjusting the height of the liquid nitrogen on the cold finger,
2. inserting an insulator around the cold finger, or
3. using a mixture of three parts liquid nitrogen to one part liquid oxygen (such as liquid air).

The optimum pressure (6) for CW xenon laser oscillation at 3.5 microns is approximately five milliTorr of xenon, slightly higher than the partial pressure of xenon in equilibrium with solid xenon at 77°K.

The corresponding optimum cryogenic temperature for operating the cold finger (to obtain the five milliTorr optimum pressure) is approximately 79°K, which explains why a mixture of liquid nitrogen (at 77°K) and liquid oxygen (83°K) performs better than pure liquid nitrogen (10).

2.2.6 Performance of LEM Xenon Laser in a Strong Magnetic Field

Although five of the 11 continuous wave (CW) xenon laser lines obtainable with the LEM xenon laser exhibited such high optical gain (when the xenon pressure and the discharge current were optimized) that they could be characterized as "super-radiant," (see Chapter 7 for a definition of "super-radiant") only three CW xenon laser lines would oscillate in a strong magnetic field ($B \approx 2000$ Gauss). These three lines were the 3.37, 3.51, and 3.99 micron xenon laser transitions. The 3.37 and 3.508 micron xenon lines split into two spectral components each, separated by approximately 7 Å for $B \simeq 5500$ Gauss. The 3.99 micron line split into two unequal components with both upper and lower frequency components displaced some 5 Å from the zero magnetic field laser oscillation wavelength ($B \simeq 5500$ Gauss). This unusual behavior was unexpected, and to date no completely satisfactory explanation has been made. The splitting of the 3.37 and 3.51 micron laser lines should be adequate to permit each of these lines to be used in the intended differential absorption application.

There are a number of alternative Zeeman-splitting techniques which might also be worthwhile developing. Some of these are:

1. Obtain higher peak magnetic fields by pulsing the magnet.
2. Obtain higher laser amplifier gains by pulsing the laser.
3. Pulse both the Zeeman magnet and the xenon laser in a synchronous fashion.

The suggested pulsed operation of the LEM Zeeman magnet would permit sweeping the oscillating laser wavelength through a range of wavelengths, $\Delta\lambda$, and also permit much higher magnetic fluxes to be obtained. A synchronized rotating combination quarter-wave plate and analyzer could double the spectral range of the Zeeman sweep while permitting instantaneous single-frequency laser operation.

The maximum pulsed magnetic field which can be generated by the present LEM solenoid is probably limited only by the inductance of the coil, the size of the pulsed current source, and the required (short) magnet pulse length. There are assoicated problems (such as back-EMF and the mechanical stresses placed on the magnet structure by the varying magnetic field), but the addition of a pulsed magnet capability to the LEM solenoid appears to be a worthwhile future addition to the experimental flexibility of the LEM system.

A pulsed noble gas laser design would likely necessitate a cold cathode construction to avoid damaging the present CW hot cathode structure. The pulsed laser design would have higher (peak) optical gain, more (peak) power, many more available laser lines (6), and would be much less sensitive to the potentially serious back-EMF associated with strong pulsed magnetic fields.

Pulsed and CW noble gas lasers geometrically similar to the LEM xenon laser have been operated by the author at more than 50 neutral laser lines in the near and middle IR regions (6). When operated in the pulsed mode, most of the observed laser lines were superradiant (using electric discharges of He/Ne, Ar, Kr, and Xe) and may be good candidates for a Zeeman-split laser application.

Additional possible LEM system modifications are described briefly below in section 7.3.2.

2.3 Magnet Design

The LEM dc Zeeman magnet is a water-cooled custom-designed solenoid subcontracted by Hughes to Tamarack Scientific Co. of Orange, California. Although it was originally intended to operate only up to fields of 5000 Gauss, the LEM magnet will briefly develop magnetic fields nearly as great as 6000 Gauss if operated at the maximum input current for a relatively short period of time (to avoid boiling the cooling water). In its present configuration, the water-cooled magnet system is connected to a closed-cycle heat exchanger cooled, in turn, by tower water available in the HAC laser laboratories. The magnet cooling water is circulated under high pressure by a large 400 psi water pump using a small 5 gallon tank as a water reservoir. The largest heat exchanger available here, a 20 kilowatt unit, is grossly overloaded when the magnet is operated at maximum field, and the cooling water boils after only a few minutes of operation. The power removed by the cooling water at maximum magnetic field is more than 80 kilowatts (approximately four times the heat exchanger capacity), and since we are only using a 5 gallon reservoir, we anticipate that the magnet can be operated at maximum field for longer periods of time if a larger heat exchanger and larger reservoir were available.

The very large welding-type air-cooled magnet power supply must be hard-wired in a permanent installation using either a 480 V 3 Ø 145 A (per phase) or a 240 V 3 Ø 145 A (per phase) power source. The cooling water source and sink (if a heat exchanger--closed cycle system is not used) should supply up to a maximum of four gallons per minute for cooling the magnet. The water pump can still be used to provide a pressure boost function when operated in a continuously-flowing mode.

Further details regarding the design and operation of the magnet can be found in sections 3.0 and 6.2 below. Assembly of the magnet system is described in section 8.2.

2.4 LEM Electronic Data-Processing System

The rack-mounted LEM Electronic Data-Processing System processes the signal output from the LEM system photodetector in order to provide direct differential abosrption data for test (absorbing) gases in the LEM Nielson-type sample cell. Two differential absorption data outputs are provided:

1. A visual readout on the dial of the digital ratiometer (at a rate of three readings per second).
2. A printed output on a chart recorder mounted in the LEM electronics rack.

The location and arrangement of the Electronic Data-Processing System components are sufficiently flexible that other connections and arrangements of the components desired by the user(s) of the LEM equipment are readily obtainable. The Electronic Data-Processing System is composed of four productized, individually rack-mounted components:

1. A high-gain dc reference amplifier mounted above the LEM Control Panel.
2. A Keithley Model 840 Autolock lock-in amplifier.
3. A Dana Model 4800 digital ratiometer and voltmeter.
4. A Keithley chart recorder.

At the present time, the lock-in circuitry operates at a frequency of 24 Hz with a provision for increasing the speed of rotation to 96 Hz by changing the drive gear ratio. The analyzer motor is a hysteresis-synchronous design locking into the 60 Hz power source.

The Autolock (Keithley Model 840) has a variable bias feature which permits it to compensate for the gross effects of non-signal ac modulation occurring at the lock-in frequency. Since the rotating prism has a component at 12 Hz due to beam steering effects, the bias feature can eliminate 2nd harmonic effects attributable to the prism beam steering.

Additional information regarding the design and operation of the Electronic Data-Processing system can be found below in sections 4.0 and 6.3.

3.0 ZEEMAN MAGNET DESCRIPTION

The large five kiloGauss water-cooled LEM solenoid is constructed of copper tubing wound on a massive aluminum bobbin. Filtered cooling water is forced through four parallel cooling channels to carry away as much as 80 kilowatts of heat generated when maximum magnetic fields are required. The cooling water is circulated (in the present design) by a massive 400 psi water pump. The magnet vendor was unaware of the actual size of the required water pump in the original design negotations with HAC, and the cost of the large water pump was not included in the magnet subcontract. The original magnet design called for ordinary tap water (at a pressure $\approx$ 60 psi) to be used for magnet cooling, and this original goal is still realizeable providing that the magnet is operated below the boiling point of the circulating water. As noted in the previous section, the high-pressure water pump vibration problem may be a serious noise problem for the LEM data-processing system, and the successful elimination of this problem is essential if the ultimate sensitivity of the LEM Zeeman absorption apparatus is to be realized.

The large electromagnet and its massive air-cooled power supply are protected by four interlock features. They are:

1. A key-lock start control,
2. Four cooling water flow switches located in each cooling water channel are interlocked, preventing or shutting-down magnet operation if insufficient water flow occurs.
3. The air-cooling fans of the magnet power supply must be operating before the magnet will energize.
4. A variable overcurrent relay interlock shuts down the magnet if a (variable) preset current limit (up to 300 A) is exceeded.

The magnetic field generated by the solenoid was carefully measured using a Hall probe, and the measured magnetic field vs. the input current are plotted below in Fig. 3-1. The z-axis variation of the magnetic field is shown below in Fig. 3-2.

Since the strong magnetic field extends well beyond the end bells

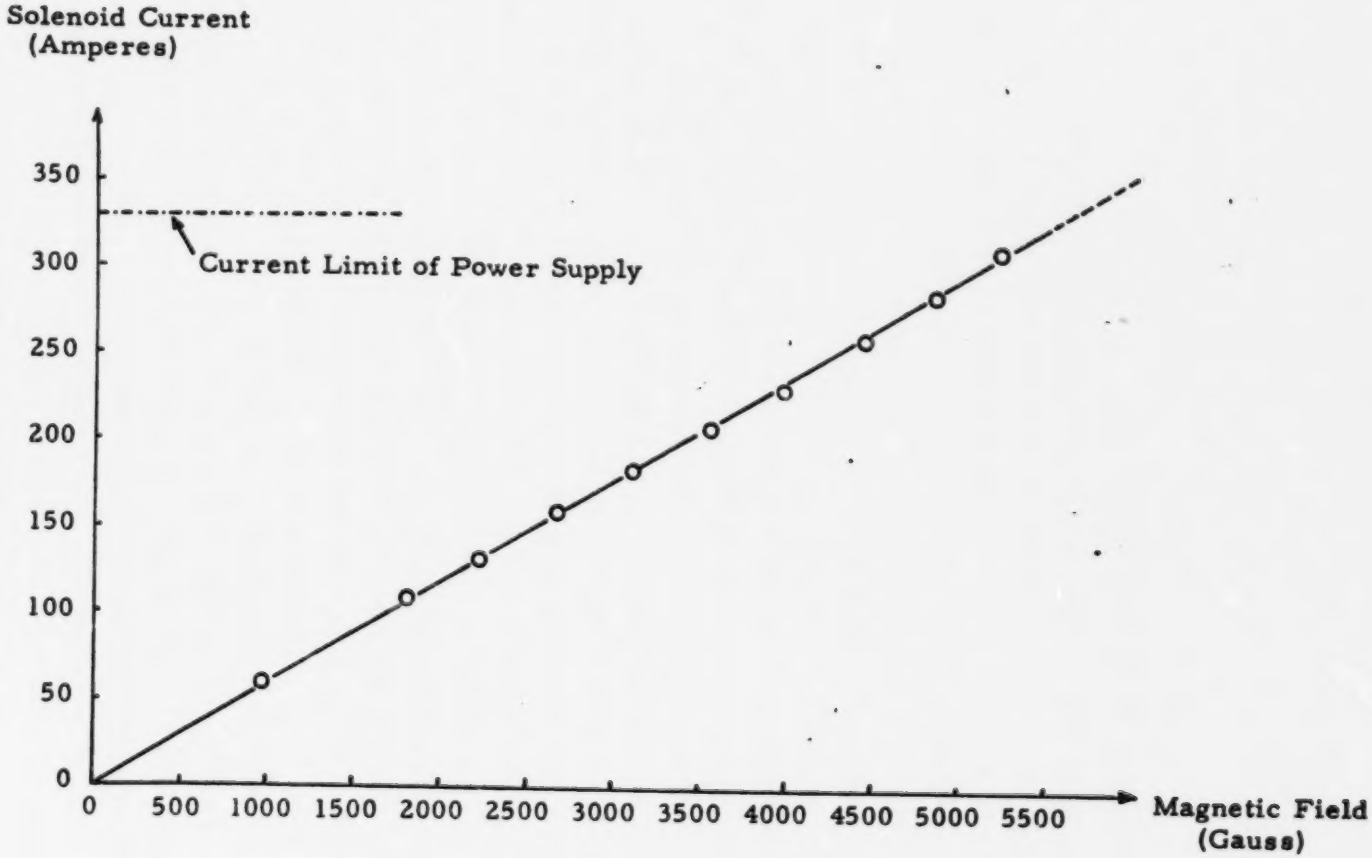

Figure 3-1 Axial Magnetic Field vs. Solenoid Current for LEM Magnet

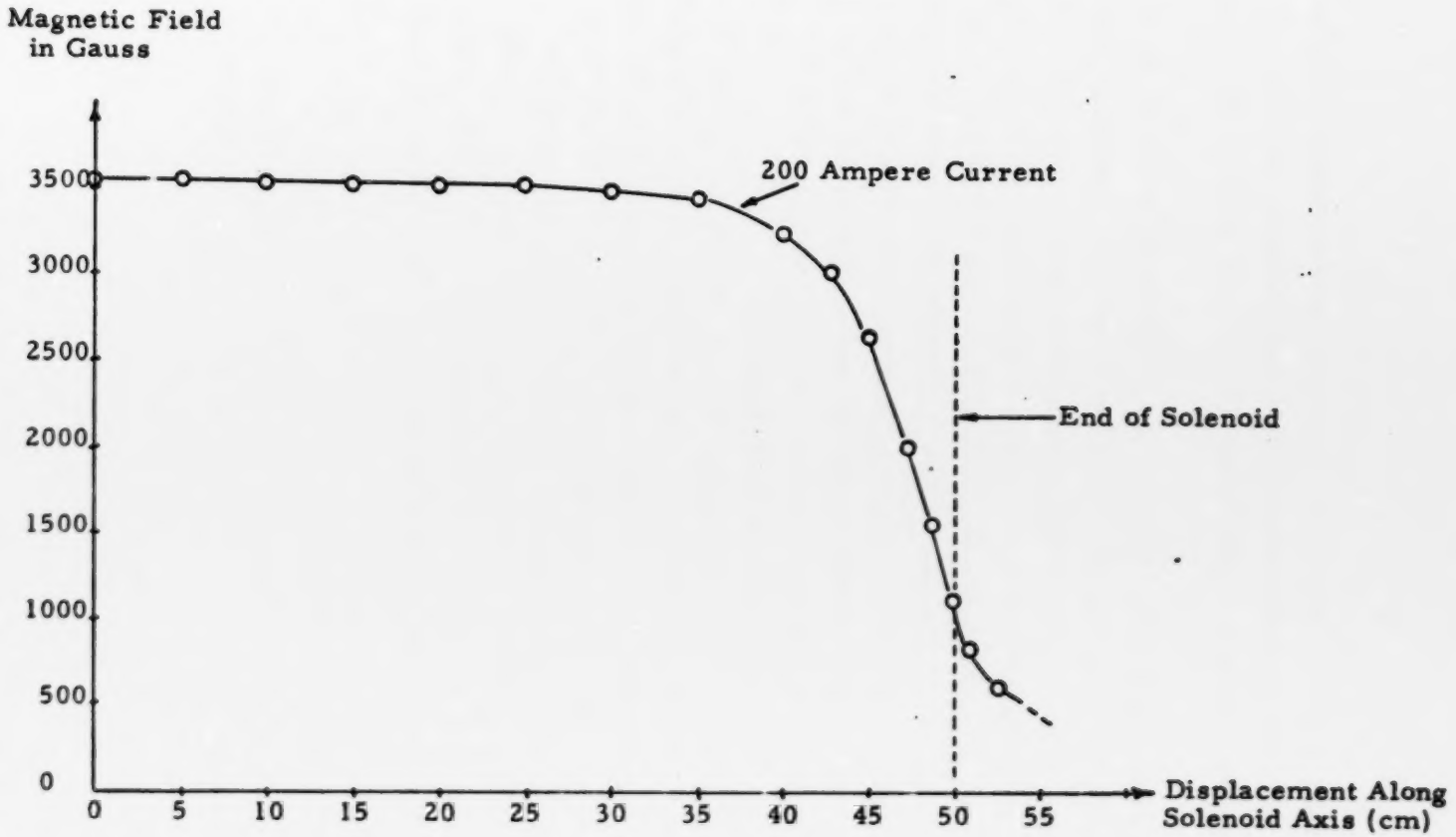

Figure 3-2 Variation of Magnetic Flux Intensity Along Solenoid Axis

of the electromagnet assembly, it is strongly recommended that all potentially affected sensitive instruments (particularly watches) be removed from the vicinity of the magnet before the large magnet is operated.

As indicated above in Fig. 2-1, the xenon laser is mounted directly inside the magnet solenoid. The xenon laser discharge tube is constructed with massive walls since it is supported only at its ends for ease of installation and removal. It has been observed that simultaneous operation of the large magnet and the CW xenon laser tends to "clean-up" (a gas-adsorption phenomenon) the xenon present in the discharge tube at a relatively high rate. Fortunately, the xenon pressure control system is able to maintain adequate xenon pressures even in the presence of the strongest magnetic fields obtainable with the magnet (up to 5500 Gauss).

The large magnet power supply does not supply a zero to 300 ampere capability. Instead, it operates continuously over smaller intervals in a series of six selectable ranges which provide an over-all current range of from 40 A to over 300 A. The output current ranges are selected at the main magnet power supply, and the continuous adjustment control variac is located in the remote control console. Details concerning magnet power requirements, cooling water requirements, space requirements, and general operation instructions are provided in section 6.

3.1 Magnet Cooling System

As shown below in Figure 3-3, the LEM magnet cooling water system is composed of eight major component types. They are:

1. A large 400 psi water pump.
2. Four parallel cooling coils.
3. Four water flow interlock switches.
4. In-line water filter.
5. Flow meter (0--10 gpm capacity).
6. Water pressure gauge (0--300 psi).

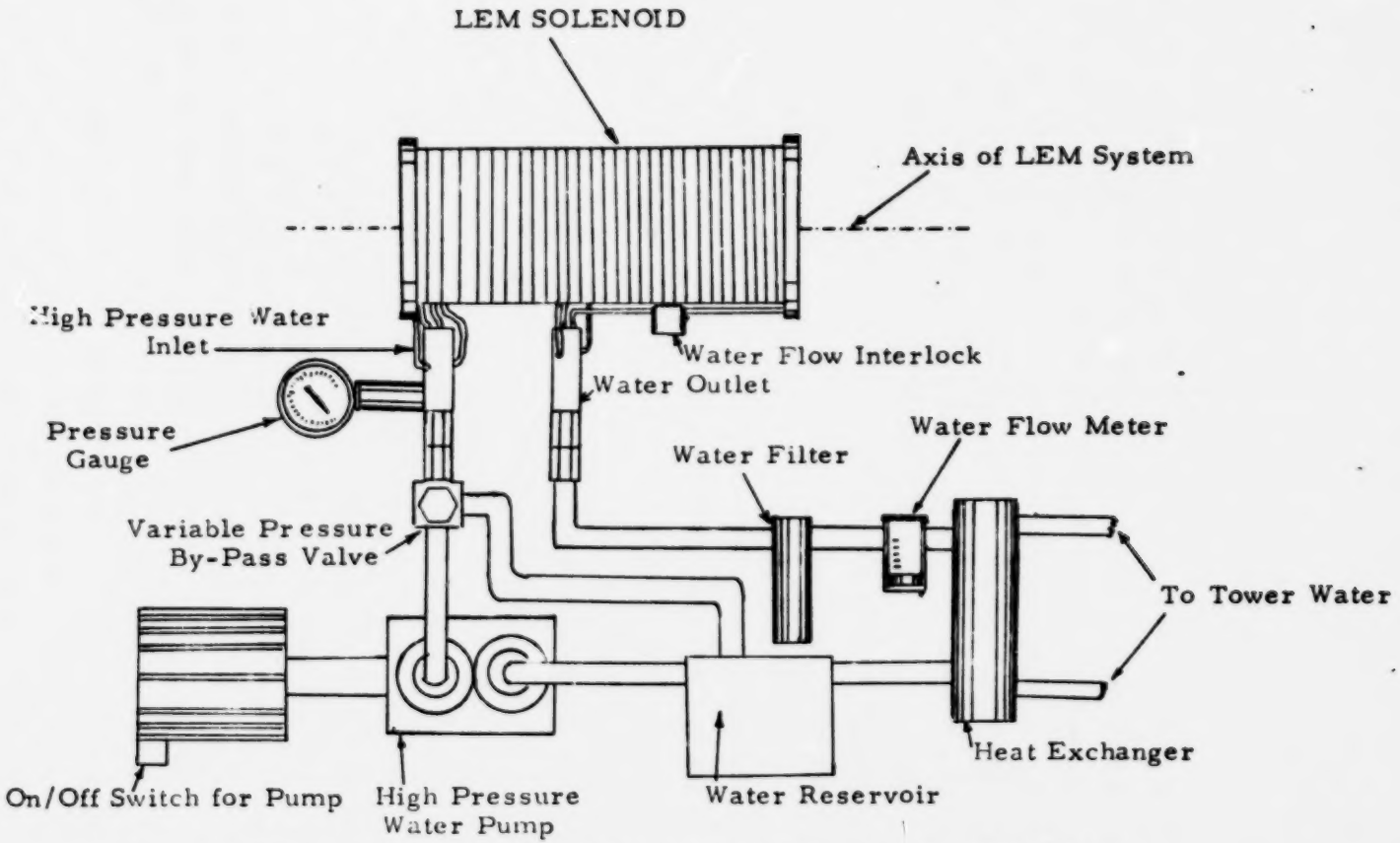

Figure 3-3 Schematic of Closed Cycle Cooling System for LEM Magnet

7. By-pass variable pressure control valve.

8. High-pressure water hoses and fittings.

It is EXTREMELY IMPORTANT to be certain that the cooling water hoses on the high-pressure side of the magnet are attached tightly according to the schematic depicted in Figure 3-3. The high pressure water, if allowed to leak, can cause serious damage to some of the optical components of the LEM apparatus (and also to certain types of ancillary laboratory equipment present). As noted in Figure 3-3, the inlet water pressure at the magnet can be adjusted from over 300 psi to approximately 100 psi using the screw adjustment on the valve.

The flow meters are individually adjustable so that different minimum flow can be selected. It will be necessary to adjust all four of the flow interlocks in sequence since all four must be operative in order to provide an "on" circuit indication to the magnet power supply.

3.2 Magnet Shutdown Procedure Precautions

When, under normal operating conditions, it is desired to shut down the LEM electromagnet, it is advisable to set the magnet solenoid current-control variac at zero and then raise the plate voltage (from 500 V to 600 V) on the LEM xenon laser to compensate for the back EMF generated by the collapsing magnetic field. If this precaution is not taken, the back EMF induced when the OFF button on the magnet control panel is pushed can extinguish the xenon laser discharge. If this happens, it is generally necessary to remove the two Allen-head screws holding the pressure-control dewar in place, and lower the dewar, thereby allowing the xenon pressure in the discharge level to rise to a sufficiently high level to permit the discharge to be reignited.

3.3 Potential Magnet Safety Hazards

The LEM magnet solenoid should not be subjected to pressures greater than 320 psi when operated with the large water pump. The

solenoid is wound with relatively heavy copper tubing, but high water pressures may cause ruptures in the water distribution manifold.

Electrical hazards in operating the LEM electromagnet are minimal since the cables are well insulated and the high voltage terminals are covered with protective sheet metal. It is, of course, expected that considerable care will be exercised in the initial wiring of the magnet power supply to prevent the possibility of a short-circuit developing.

Separate instruction manuals for the magnet, flow rate interlocks, and magnet power supply are included as detached appendices of this Final Report.

4.0 ELECTRONIC DATA-PROCESSING SYSTEM

The details of demodulating the Zeeman-split xenon laser beams (together with their associated differential absorption data) were presented above in section 2.2.3. The present section is concerned with a general description of the component configuration and over-all arrangement of the electronic components comprising the LEM Electronic Data-Processing System.

A block diagram of the Electronic Data-Processing System is shown below in Figure 4-1. The dc and ac components present in the output of the photodetected signal are separated and individually amplified by the dc amplifier and lock-in amplifier respectively. Prism phase information is obtained by the use of a magnetic pick-up mounted on the prism analyzer mechanism and fed into the reference channel of the lock-in amplifier circuitry. After the lock-in amplifier is suitably synchronized with the ac (differential absorption) signal, the amplified output from the autolock amplifier is fed into the digital ratiometer where its amplitude is compared at a rate of 3 Hz with the output from the dc amplifier. The output from the digital ratiometer then drives the chart recorder.

The present HAC laser facility is limited by safety requirements regarding the use of toxic gases, and hence the actual calibration of the differential absorption by formaldehyde has not been possible, and it is presumed that this calibration procedure will be carried out at the EPA facility after delivery of the LEM equipment.

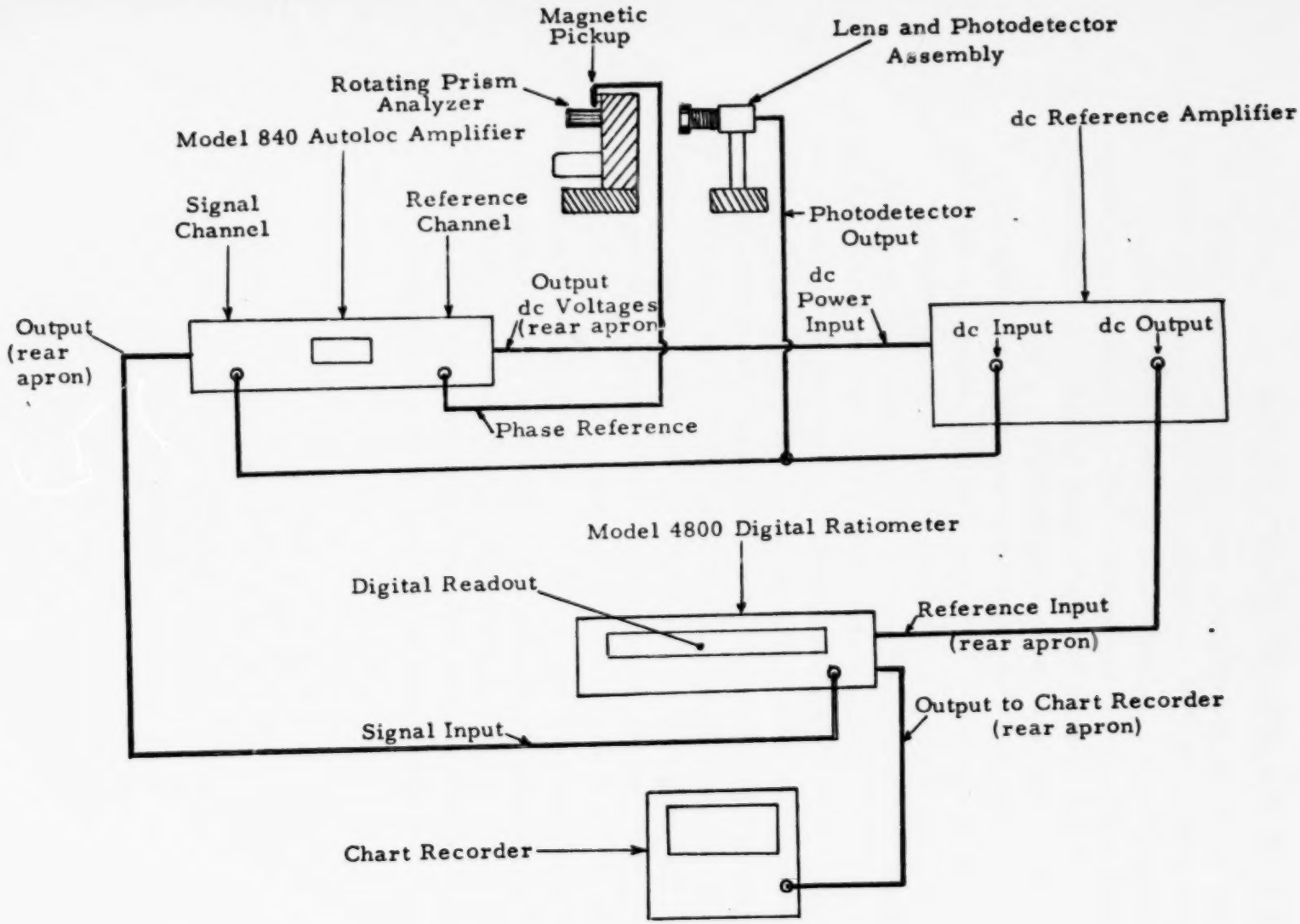

Figure 4-1 Block Diagram of Electronic Data-Processing System

5.0 ALDEHYDE SAMPLE CELL

The Aldehyde Sample Cell is basically a heated vacuum cell constructed of stainless steel in a "T" configuration. A small reservoir of paraformaldehyde located in the bottom of the "T" is heated until a suitably high vapor pressure of HCHO is obtained. The sample cell heater control is a variac located in the LEM equipment rack.

The sample cell windows are uncoated CaF_2 flats, and hence both the 3.5 and the 5.6 micron absorption bands of HCHO can be investigated (5) using the sample cell and the xenon lines at 3.508 and 5.57 microns. The filling port of the Aldehyde Sample Cell is fitted with a vacuum valve for evacuating the cell or for filling the cell with a suitable (absorbing) sample gas. Since the cell is mounted on an optical bench slide, it can readily be removed from the LEM apparatus and filled elsewhere. The vacuum line attached to the sample cell is a standard 1/8" vacuum tubulation for evacuation of the cell.

Vacuum sealing of the sample cell is accomplished with "O" ring seals at the two windows and at the filling port. At present, no provision has been made to prevent the condensation of paraformaldehyde on the sample cell windows, and thus the heater control must be adjusted carefully to prevent vaporizing too much of the parent chemical.

6.0 OPERATION INSTRUCTIONS FOR LEM APPARATUS

The following LEM operation instructions are given in the order appropriate for conducting an aldehyde absorption measurements. The user(s) of the LEM apparatus are strongly urged to COMPLETELY READ these Operation Instructions before actually attempting to operate the LEM equipment. Serious damage can occur to the individual LEM system components if specific operational procedures are not followed. The following sections describe in detail the proper step-by-step procedures to be followed for placing in operation each major LEM system component.

6.1 Xenon Laser Operation

The following procedure must be followed in the order indicated to prevent possible permanent damage to the LEM xenon laser.

1. SLOWLY advanced the CATHODE CURRENT control until a laser cathode heater current between 9 and 10 amperes is indicated on the cathode current ammeter mounted on the LEM CONTROL PANEL. Allow approximately 5 minutes for the cathode to come up to temperature. A normal setting for the LASER CATHODE CURRENT variac is a dial reading of 44 when the cathode has reached its equilibrium temperature. To avoid thermally shocking the heavy cathode structure, DO NOT exceed a current of 10 amperes during the warm-up phase. The cathode must be at operating temperature (1300^{o}K) before the dc excitation voltage is applied to the anode in order to avoid possible ionic bombardment (and consequent sputtering of barium from the cathode structure). The HP dc high voltage supply (located directly under the Autolock amplifier in the electronics rack) should be OFF, and the pressure-control dewar mounted under the laser cathode assembly should either be EMPTY or removed from the cold finger assembly.
2. With the laser cathode at temperature (bright orange heat), set the dc voltage on the HP power supply to 500V. Turn the dc voltage ON. Press and release the LASER START button. The laser discharge tube should ignite and draw approximately 30 mA current. This level of discharge current is indicative of relatively high xenon pressure in the laser tube--CW laser oscillation will NOT occur at this pressure.

3. Be certain that the xenon laser pressure-control dewar is fully raised around the cold finger assembly loca ted directly under the laser cathode bottle. Pour in a few hundred milli-liters of liquid nitrogen to cool the dewar walls down to 77°K. After the dewar walls are cool, add a sufficient quantity of liquid nitrogen until the equilibrium level of the liquid nitrogen in the dewar is approximately half way up the length of the cold finger. (It is important NOT to fill the pressure-control dewar with liquid nitrogen before the laser cathode is hot and the xenon discharge is ignited. If the dewar is filled first, the xenon pressure in the discharge tube quickly drops below the minimum pressure required to establish an electric discharge.) The xenon laser can now be operated without using the pressure-control electronics; details on the use of this control are given below in section 7.2.

After a period of from 5 to 10 minutes, the remaining xenon pressure in the discharge tube should be sufficiently low to permit CW laser oscillation to occur, and the laser discharge current should be between 50 and 70 mA with the dc power supply voltage set at 500 V. The relative output power of the laser can be directly measured using the output signal from the InAs photodetector. When the photodetected output is connected to a dc microvoltmeter (such as a HP 425 microvoltmeter) or a dc oscilloscope, it is possible to perform the laser cavity mirror alignment operation described below in section 7.3.

If the xenon electrical discharge is extinguished accidentally, and if the LASER START button does not reignite the laser tube, it will be necessary to lower the pressure-control dewar until the cold finger no longer is in contact with the bath of liquid nitrogen. After a sufficient quantity of xenon sublimes from the cold finger, it will be possible to reignite the laser tube commencing with step 2., above.

Measurements of the laser output power, wavelengths of oscillation, and radiance should be made after the laser cavity mirror alignment has been optimized. As discussed below in section 7, a number of the CW xenon laser lines obtainable with the LEM apparatus are quite sensitive to xenon pressure and discharge current--these lines tend to be of lower over-all optical gain, and consequently these lines also

require nearly perfect laser cavity mirror alignment before they can be obtained at all. Although a small 1/4 meter spectrometer can be used to measure the approximate wavelengths of the xenon laser lines present in the output spectrum, an instrument of higher resolution will be required to clearly separate the two Zeeman components of the several xenon lines which oscillate in very strong (5000 Gauss) magnetic fields. The instrument used for these measurements at HAC was a 3/4 meter Czerny-Turner spectrometer. It is, of course, important also to use a suitable middle infrared photodetector when laser lines of longer wavelength than 3.51 microns are to be examined (such as an InSb detector). The InAs photodetector furnished with the LEM apparatus is optimized for the 3.51 micron laser line, and has, in general, insufficient spectral response to detect laser lines beyond 3.68 microns.

If it is desired to measure the output power of the xenon laser, a calibrated thermopile can be inserted in the laser beam and the output signal displayed on a microvoltmeter. Output powers of from five to ten milliwatts at 3.51 microns are nominal, with proportionally smaller output powers available at the other nine lines.

Potential Problem Areas--Cathode

The hot cathode structure of the xenon laser is a well proven, long-lived design. It can, however, be damaged by poor operating procedures. The most serious danger to the cathode (aside from compromising the vacuum envelope of the laser tube) is from bombardment by heavy ions. This bombardment can occur if:

1. the temperature of the cathode is too low when the laser tube is conducting,
2. the discharge current is too high, or
3. the emissivity of the cathode is low.

It is quite evident when the cathode is undergoing bombardment: the electric discharge is visibly in contact with the hot cathode. Normal cathode operation is evidenced by a "cathode stand-off"distance of at least one and preferably two centimeters. If the xenon laser cathode

is observed to be thus enveloped by the xenon discharge, corrective action must be taken promptly to avoid damaging the cathode permanently. Corrective measures include: lowering the laser excitation voltage (thereby reducing the discharge current), raising the cathode heater current (thereby increasing the thermionic output from the laser tube cathode), or if these measures are not adequate, the high voltage supply should be shut off and the laser allowed to operate in a stand-by mode for at least thirty minutes. If, after re-establishing the electric discharge, the cathode does not have adequate emission, it has already sustained damage and will require either replacement or, at the very least, reprocessing. If the indicated operating procedures are scrupulously followed, however, it is expected that the hot cathode structure in the xenon laser will give years of dependable service.

Another possible difficulty which could develop is failure or rupture of the vacuum envelope. Obvious evidence of this problem will be a badly discolored (generally white--gray) cathode bottle, particularly in the vicinity of the barium getter assembly located in the upper portion of the cathode bottle. Under no conditions should the cathode be heated if the cathode bottle turns white since such an indication is evidence of atmospheric oxygen present in the cathode bottle. If the cathode is cool when such an accidental rupture occurs, it may be possible to reprocess the cathode after the rupture is found and corrected. Otherwise, a new cathode and complete tube reprocessing will be required to correct the problem. Since the LEM laser tube is equipped with expensive "V" anti-reflection coated 0^{o} sapphire windows, it is important to handle the laser tube with care even if a vacuum failure occurs.

It is extremely unlikely that other problems can cause malfunction of the xenon laser tube. The pressure-control system is designed to be a fail-safe system, and hence it should never be necessary to rework the cryogenic pressure-control subsystem since it can readily be turned off and back-up techniques instead. Additional details concerning the physics of xenon laser operation can be found

in Chapter 7.

Limitations on Xenon Laser Tube

The maximum obtainable output power from the xenon laser is approximately proportional to the plasma tube discharge current (if the xenon pressure is near the optimum value). Restrictions, however, are placed on the maximum discharge current to prevent premature failure of the LEM xenon laser. Although the LEM xenon laser is a well-proven durable design capable of many thousands of operational hours, there are three principal causes for possible premature failure of this type of laser tube:

1. Physical damage to the vacuum envelope due to impact or excessive strain (particular care must be taken when the dc magnet is operating to prevent magnetic materials from being drawn into the fragile xenon laser tube).
2. Damage to the hot cathode structure (usually through ionic bombardment).
3. At the lowest xenon pressure obtainable with the cryogenic pressure control system, it is possible to generate an electron beam of sufficient intensity to burn a hole through the vacuum envelope of the cathode bottle. This danger can be minimized and cathode life prolonged by operating the xenon laser at discharge currents of 50 mA or less.

The present LEM xenon laser design uses a 5,000 Ω power load resistor in series with the xenon plasma tube, and operation of the xenon laser with the present load resistor at currents of 25 mA or less may cause the electric discharge to become unstable due to insufficiently high plate voltage. If it is desired to operate the xenon laser at even lower discharge currents than 25 mA (to prolong the life of the xenon laser), power load resistors of 10 or 20 kΩ may be substituted for the present load resistor.

6.2 Magnet Operation Procedure

6.2.1 Introduction

The large five kiloGauss LEM electromagnet is protected by four interlocks which are designed to protect the magnet and its associated power supply from damage. In order to place the magnet in operation, it is necessary to satisfy all the interlock requirements. The interlocks are:

1. Master control key-lock on/off switch.
2. Four cooling water flow interlocks.
3. Magnet power supply cooling fan interlocks.
4. Variable magnet overcurrent interlocks.

The key-lock prevents unauthorized operation of the magnet system. Each of the water flow interlocks must be adjusted for the lowest acceptable water flow level that will be used. It will be evident if a given level of water flow is inadequate for a given input power to the magnet solenoid; namely the cooling water will commence boiling, and the water flow will decline, which, in turn, will cause the water-flow interlocks to shut down the magnet power supply. The maximum dc magnetic field developed by the LEM electromagnet is primarily limited by the level of water-cooling available for magnetic fields less than five kiloGauss. Thus the approximate upper range of the magnetic field to be generated must be decided before the magnet is energized. The appropriate CURRENT RANGE of the magnet power supply must also be selected at this time. Three current ranges are available for both 460 and 230 V ac power supply wirings. These ranges are:

1. 80--140A (460V ac)	1'. 40--70A (230V ac)
2. 90--200A (460V ac)	2'. 45--100A (230V ac)
3. 100--330A (460 V ac)	3'. 50--165A (230V ac).

If the large LEM cooling water pump (generating a water pressure of 300+psi) is used, closed cycle cooling operation is possible for maximum magnetic field generation, providing that the associated (closed cycle) heat exchanger has adequate capacity (80--100 kilowatts).

If only tap cooling water is available (and no external heat exchanger), the exhaust water must be dumped, and the lower pressure (probably only 60 psi) will require that the maximum magnetic field be reduced by approximately a factor of $\sqrt{5}$.

As in the case of the Operation Instructions provided above for the Xenon Laser, the following step-by-step procedure should be carried out in the order indicated.

6.2.2 Operation Instructions

Step 1. Turn ON the magnet key interlock located on the remote control console.

Step 2. Turn ON the cooling water supply to a sufficiently high flow rate to cool the magnet adequately and also activate the water flow interlocks. The water-flow interlock lights on the remote control console should turn from RED to GREEN.

Step 3. Turn ON the magnet power supply cooling fans.

Step 4. Press the OVERCURRENT RESET button if the overcurrent warning light is RED. The overcurrent GREEN light should turn on.

Step 5. If all control lights are GREEN, then press the green MAGNET ON button to energize the LEM electromagnet.

Step 6. Adjust variac on magnet remote control console to the desired current level. See Figure 3-1, above, for a calibrated curve of input current vs. axial magnetic field.

Step 7. Check magnet temperature frequently at first (at least at five minute intervals) to prevent overheating of the magnet. The water flow interlocks will shut down the magnet power supply if the water begins to boil, but this situation should be avoided if at all possible.

6.2.3 Selecting Magnet Current Range

The three magnet current ranges (at 480 and 240 V 3 Ø) are selectable at the main magnet power supply under the small, hinged front door. A wiring diagram attached to the protective door clearly indicates the proper arrangement of the current-selecting bars.

6.3 Electronic Data-Processing System Operating Procedure

The LEM Electronic Data-Processing System consists of four individual units. They are:

1. High-gain dc reference amplifier.
2. Keithley Model 840 "Autoloc" amplifier.
3. Dana Model 4800 digital ratiometer.
4. Keithley Chart recorder.

Interconnection of these individual units should follow carefully the block diagram shown above in Figure 4-1. The photodetected output from the InAs photodetector is connected (via BNC cables of the appropriate length) to the + INPUT of the Model 840 and to the DC AMPLIFIER INPUT of the dc reference amplifier. The BNC cable from the magnetic pickup mounted on the LEM prism analyzer assembly should be connected to the INPUT of the Model 840 reference channel. The OUTPUT from the Model 840 should be connected to the INPUT of the Model 4800 located on the right side of its front panel. The OUTPUT from the dc Reference Amplifier should be connected to the INPUT of the Model 4800 located on the rear of its chassis (REF.). The OUTPUT of the Model 4800 is used to drive the Chart Recorder and should be appropriately connected.

If an aldehyde absorption measurement is desired, the CW xenon laser should be turned on (according to the procedure described above in section 6.1), the LEM electromagnet should be energized (following the instructions outlined above in section 6.2), and the vacuum sample cell (or other test cell) should be filled with a sample absorbing gas and placed in the optical path of the LEM system.

When the LEM apparatus has been prepared for operation, then the Electronic Data-Processing System should have its controls turned to the following settings:

KEITHLEY model 840:

Power: ON; AC SENSITIVITY: 10 mV; DC SENSITIVITY: x100; TIME CONSTANT: 100 ms; ZERO SUPPRESS: OFF; FREQ BAND HZ: 100 Hz; TRIGGER: (-)

DANA Model 4800:

POWER: ON; RANGE: 10V/dc; FRONT/REAR: Front;

Press the following control buttons: DATA OUTPUT, PERIODIC, and RATIO.

When these units are interconnected as indicated and the individual controls set in accordance with the above directions, then the Electronic Data-Processing System is ready to analyze the photodetected output of the LEM apparatus. For the purpose of illustration, we assume that the ac (differential absorption signal) component from the photodetector (with a periodicity twice that of the rotational frequency of the analyzer prism) has an amplitude only 10^{-3} that of the dc (total laser output) signal. If we assume that the dc signal has a 50 mV level, then the ac signal must be 50 μV. Under these conditions, the AC SENSITIVITY of the Model 840 can be increased to either 0.1 or 0.01 mV and the DC SENSITIVITY adjusted to give about a one-half scale reading on the dc METER of the Model 840. The PHASE control is then adjusted to maximize the signal detected on the dc METER. It may be necessary to decrease the DC SENSITIVITY if the METER displays an off-scale reading. In addition, the OVERLOAD light will turn on if the METER displays an off-scale reading. When the Autoloc amplifier is properly phase-locked, the signal on the METER should be quite stable. The RATIO control button on the Model 4800 can also be deactivated permitting the Model 4800 to be be used as a digital dc voltmeter. Under these circumstances, the output from the Model 840 can be displayed at a 3 Hz rate.

7.0 DETAILS OF LEM XENON LASER OPERATION AND ADJUSTMENT

The successful operation of the LEM apparatus is strongly dependent upon the adequate performance of the LEM xenon laser. This Final Report provides information and operating procedures for optimizing xenon laser performance in a total of four locations. A brief discussion of the spectral broadening, longitudinal mode structure, and general oscillation characteristics in and out of an axial magnetic field was presented above in section 2.2. The general procedure for operating the LEM xenon laser can be found above in section 6.1. Details concerning the initial assembly and wiring of the LEM xenon laser are provided in section 8.1, below.

The present section is intended to provide an adequate amount of information to optimize operation of the LEM xenon laser at all of the available CW xenon laser wavelengths. Eleven CW laser lines can oscillate simultaneously in the LEM xenon laser, and the different requirements of each of these lines are described in this section. Accordingly, the following areas are treated:

1. Physics of xenon laser oscillation.
2. Optimization of xenon laser lines.
3. Laser cavity properties and alignment procedures.

Each of these sections is described below.

7.1 Physics of Xenon Laser Oscillation

The major laser lines obtainable with the LEM xenon laser are high optical gain, low output power transitions. Although relatively high peak output power can be obtained from pulsed TEA noble gas lasers (particularly xenon TEA lasers) at approximately the same transitions as the CW low power (and low pressure) noble gas lasers, for the purposes of the present application the low power CW laser configuration should be entirely adequate. Most treatments of CW laser oscillation are concerned with the oscillation of laser lines exhibiting relatively low optical power gains (of the order of only a few dB/meter), and although, in general, the oscillation characteristics

of high-gain lasers are quite similar, there are some important differences which require special mention. In this section, the general conditions for the establishment of laser oscillation with a typical high-gain xenon laser line will be described and mention will be made (where appropriate) of the weaker, low gain lines also obtainable with the LEM xenon laser.

The optical power gain of a laser amplifier is given by

$$G_o = e^{\sigma N \ell} \qquad (7\text{-}1)$$

where σ is the stimulated emission cross-section of the laser transition, N is the inversion density, and ℓ is the active length of the laser amplifier. G_o represents the "small signal" power gain obtained by passage of a beam of low intensity once through the laser cavity. In actual practice, the optical power gain of a laser amplifier "saturates" down to a level equal to the optical losses in the laser cavity, and equation (7-1) holds in this case also when the average inversion density, N, replaces the peak inversion density, N, in equation (7-1). The stimulated emission cross-section, σ, is a convenient parameter which contains the physical parameters related to the relative line strength, wavelength, linewidth, etc., of the laser transition:

$$\sigma(\nu) = \left\{ \frac{\lambda^2}{\tau_3 8\pi} \right\} g(\nu - \nu_o) \qquad (7\text{-}2)$$

Here τ_3 is the lifetime of the upper laser level and $g(\nu - \nu_o)$ is the Gaussian gain function of the Doppler and isotope-broadened linewidth:

$$g(\nu - \nu_o) = \sqrt{\frac{4 \ln 2}{(\Delta\nu_D)^2}} \quad \exp\left[- \frac{4 \ln 2 (\nu - \nu_o)^2}{(\Delta\nu_D)^2} \right] \qquad (7\text{-}3)$$

where $\Delta\nu_D$ is the Doppler-broadened spectral width of the laser transition. For frequencies near $\Delta\nu_o$, i. e., near line center, equation (7-3) reduces to

$$g(0) = \frac{0.92}{\Delta\nu_D} \approx \frac{1}{\Delta\nu_D}$$

so that the peak stimulated emission cross-section, σ_o, can be written as

$$\sigma_o = \frac{\lambda_o^2}{8\pi\, \tau_3\, \Delta\nu_D} \qquad (7\text{-}4)$$

An alternative definition for σ in terms of the "oscillator strength" of the laser transition is given by

$$\sigma = \left[\frac{g_3}{g_2}\right] \frac{e^2}{Fmc} \quad f_{32} \qquad (7\text{-}5)$$

where g_2 and g_3 are the degeneracies of levels 2 and 3 of the laser transition, e is the electronic charge, m is the mass of the electron, F is the spectral cross-relaxation rate, and f_{32} is the oscillator strength of the laser transition.

The high-gain xenon laser transitions in the case of the LEM laser are characterized by having large stimulated emission cross sections (σ), relatively small population inversion densities (N), and, of course, all the same active length; in the present case, the active length of the LEM laser is approximately one meter. The small population inversions obtained with these lines is indicative of the relatively low CW laser power obtainable with these xenon laser transitions. A measure of the relative power extractable from a laser oscillator is the magnitude of a parameter often referred

to as the "saturation flux" defined by

$$\phi_s = \frac{h\nu}{\sigma \tau_3} \qquad (7\text{-}6)$$

where h is Planck's constant. In practice, ϕ_s is the input flux to a laser amplifier necessary to saturate (lower) the small signal optical power gain, G_o, by 3 dB. On the average, low pressure gas lasers have small values of ϕ_s (corresponding to very large values of σ) and are consequently, essentially low-power devices. Solid state lasers have large values of ϕ_s, and are high-power devices.

7.1.1 Establishment of Laser Oscillation

It is often convenient to treat the active medium of a laser as an optical amplifier (11); i. e., by analogy with an electronic amplifier, an optical amplifier has a definite optical gain and a related background optical noise level (in the case of high-gain laser amplifiers). The optical power gain is defined most simply as the ratio of the input power to the output power of the laser amplifier in the limits of small input power and unsaturated amplifier conditions. The "optical noise" property of the laser amplifier is due to amplified spontaneous emission (12). This "noise" property of laser amplifiers is inherent and presents little or no problems in low-gain lasers but assumes great importance for high-gain laser amplifiers. Depending upon the gain of the laser amplifier, spontaneous emission can ultimately limit the maximum single-pass gain obtained in a laser amplifier. Thus, when a laser amplifier is adjusted in such a fashion that the spontaneous output along the axis of the laser equals the saturation flux of the laser medium, the laser amplifier enters the so-called "superradiant" condition.

When operated in the superradiant limit, the high-gain laser amplifier can emit substantial optical power without requiring an external resonator cavity; i. e., "oscillation" without mirrors is possible. It is possible, using a simple geometrical model, to

predict when a given high-gain laser amplifier will enter the superradiant limit. If the small signal amplifier gain is given as G_o, then the maximum superradiance-limited optical gain is given by the inequality

$$\frac{G_o}{\sqrt{\ln G_o}} \leq \frac{4\pi}{\Omega} \qquad (7\text{-}7)$$

where Ω is the solid angle self-subtended by the laser amplifier and the $\sqrt{\ln G_o}$ term is due to the spectral narrowing effected by the passage of the spontaneously-emitted photons through the high-gain laser amplifier

In the case of the strong xenon laser lines listed in Table 2-1, above, nearly all of them are superradiance-limited according to the inequality given above in expression (7-7). As a consequence, these laser lines have output power characteristics that are not very strongly influenced by the quality of the laser cavity mirror alignment, and, as discussed below in section 7.3, these lines should not be used as sensitive indicators of the final adjustments on the LEM xenon laser cavity mirrors. A superradiant laser is relatively easy to align, however, since it emits a considerable amount of laser radiation even when the cavity mirrors are not well adjusted.

In general, there are three basic conditions for a (low-gain) laser to commence oscillation:

1. The square of the single pass small signal gain, G_o^2, must be greater than the reciprocal of the cavity regeneration efficiency, $1/\xi$:

$$G_o^2 = e^{2\sigma N \ell} \geq \frac{1}{\xi} \qquad (7\text{-}8)$$

2. A resonant TEM cavity mode must lie within the Doppler-broadened spectral gain distribution. The small signal gain, G_o, at this frequency must satisfy the inequality (7-8).

3. A means must be provided to maintain the population inversion density, N, at a sufficient level to maintain CW laser action (if CW oscillation is required).

The cavity regeneration efficiency, ξ, is the product of all the laser cavity mirror reflectivities, window and atmospheric transmissions, diffraction and polarization efficiencies, etc. of the round trip optical path in the particular laser cavity used. According to this simple theory, if the square of the laser amplifier small signal gain is not greater than the reciprocal of the cavity regeneration efficiency, then laser oscillation will not commence, and the laser amplifier emits only a relatively small quantity of essentially amplified spontaneous emission. It is evident from expression (7-8) that these high-gain laser lines of xenon can be used in laser cavities of relatively low optical efficiency; this property is very useful if high-loss, long optical paths are used to detect relatively small molecular concentrations (9, 13).

If the optical gain of a laser amplifier is not at the superradiant limit defined above by expression (7-7), then the onset of laser oscillation once the "threshold" condition is met (expression (7-8), above) is abrupt, with a large increase of circulating optical power in the laser cavity. This "threshold" of oscillation property of moderately-high gain lasers can be used to advantage if absorption spectroscopic techniques are used to vary the losses in the laser cavity on each side of laser oscillation "threshold."

7.1.2 Saturation of Laser Amplifier Gain

The inequality indicated in expression (7-8) above represents a non-equilibrium situation which applies only during the build-up of laser oscillation. This build-up of laser oscillation essentially starts with the circulating flux in the laser cavity consisting only of spontaneous emission. As each transit through the laser cavity amplifies the circulating spontaneous emission by the excess of amplifier gain over the loss coefficient (calculated from $\ln \xi$),

the circulating power in the laser cavity eventually reaches the "saturation flux" level defined above in expression (7-6). At this level of optical flux, the small signal gain, G_o, of the laser amplifier has begun to "saturate," and when the circulating flux has reached a value near ϕ_s, the small signal gain has declined by approximately 3 dB. For steady-state, continuous wave (CW) laser oscillation, the optical power gain, G, of the laser amplifier saturates to a level given by the optical regeneration efficiency defined above; namely:

$$G_s = e^{\sigma N_s \ell} \qquad (7\text{-}6')$$

The steady-state inversion density, N_s, can readily be obtained from the above relation. In general, however, this simple theory is inadequate if relatively high output powers are obtained, since the stimulated emission cross-section and the saturation flux depend on additional parameters including the output power (and, consequently, the stimulated emission rate).

In the case of the 3.51 micron xenon laser transition and the typical conditions that apply to operation of the LEM apparatus, the onset of laser oscillation occurs very rapidly since the laser transition exhibits very high optical gain (as much as 30 dB/meter) together with a relatively low saturation flux (of the order of 10 milli-watts/cm^2). Output power fluxes of the order of 0.1 watts/cm^2 can be obtained at 3.51 microns if all the laser amplifier and cavity parameters are optimized (for low pressure operation), but the low pressure, CW xenon laser is inherently an inefficient device. A large part of the inefficiency of the xenon (and, correspondingly neon, argon, and krypton) laser is due to the fact that it is necessary to excite a neutral xenon atom nearly to the ionization limit in order to reach the first excited states. The stored energy in the excited state is only partially extracted during laser oscillation since the lower laser level itself is near the ionization limit.

7.2 Optimization of Xenon Laser Lines

The optimization of each of the ten xenon laser lines obtainable with the LEM xenon laser can be carried out by adjusting the xenon pressure and discharge current to values appropriate for each laser transition. It is possible to obtain simultaneous oscillation of all ten xenon laser lines since these lines do not compete for the same population inversions. In general, however, not all of these lines will oscillate simultaneously under ordinary operating conditions since some lines require lower pressures than others, better laser cavity alignment, more or less discharge current, etc. The general ranges of optimum xenon pressures to be used for each of these ten CW laser lines are listed above in Table 2-1. In this table, "low" xenon pressure is obtained by having no current input to the heater of the cryogenic pressure-control cold finger. "Moderate" xenon pressure is obtained by either applying sufficient heater current to the cold finger heater or by lowering the level of liquid nitrogen in contact with the cold finger. This latter pressure-control technique can be readily accomplished by removing the two Allen cap screws which secure the liquid nitrogen dewar under the xenon laser cold finger assembly. A lab-jack (or similar dewar height adjustment device) can then be used to vary the contact height of the liquid nitrogen bath.

If the xenon laser tube electric discharge is accidentally extinguished with the liquid nitrogen in the pressure-control dewar, it may be necessary to lower the dewar completely in order to increase the xenon pressure to a level sufficient to reignite the electric discharge. In addition, it is likely that condensation of moisture from the atmosphere will require the emptying of the pressure-control dewar of accumulated water, possibly as often as every day of regular operation.

7.2.1 Spectroscopic Details of Xenon Laser Transitions

The 11 xenon laser transitions listed above in Table 2-1 are described in terms of Racah spectroscopic notation (14) applicable to the j--l coupling scheme used to describe the energy levels in

heavy noble gases. The primed energy levels in Table 2-1 refer to the $^2P^o_{1/2}$ parent ion and the unprimed energy levels refer to the $^2P^o_{3/2}$ parent ion of xenon. Theoretical calculations of the relative line strengths of most of these laser lines have been carried out (15), although transitions between the terms of the $^2P^o_{1/2}$ and $^2P^o_{3/2}$ parent ions are treated as forbidden. As indicated in Table 2-1, both the 3.62 and the 4.15 micron xenon laser lines are such "forbidden" intercombination lines. Although these lines tend to be somewhat weaker than the "allowed" CW xenon laser lines obtained with the LEM laser, they are not significantly weaker than the strongly "allowed" 3.86 micron line listed in Table 2-1. Aside from these two intercombination lines, the strong CW xenon laser lines follow the theoretical calculations (15) quite closely, as indicated by the calculated line strengths listed in the last column of Table 2-1. Laser lines arising from transitions in the term scheme of the $^2P^o_{1/2}$ ion tend to have lower gain and lower output power owing to the lower multiplicity of the parent ion.

7.2.2 Effects of Xenon Pressure on LEM Laser Output Power

It has been mentioned above that optimum xenon pressures and discharge currents can be found for each of the ten CW xenon laser lines obtainable with the LEM apparatus. These optimum xenon pressures are obtained by varying the temperature of the cryogenic pressure-control cold finger, and a number of techniques for effecting this temperature variation have been suggested above in sections 6.1 and 7.2. Although the xenon pressure control is designed to permit continuous pressure control over the range from 2 to several hundred milliTorr, the optimum xenon pressures for all the CW laser lines obtainable with the LEM apparatus lie below 20 milliTorr.

An approximate indication of the xenon pressure present in the LEM xenon laser discharge tube at any one time can be obtained from the impedance characteristics of the electric discharge. As shown below in Figure 7-1, using a (standard) voltage of 500 V on the tube anode, the (standard) 5,000 Ω power load resistor, a pressure of several milliTorr produces the highest current (75 mA), while a

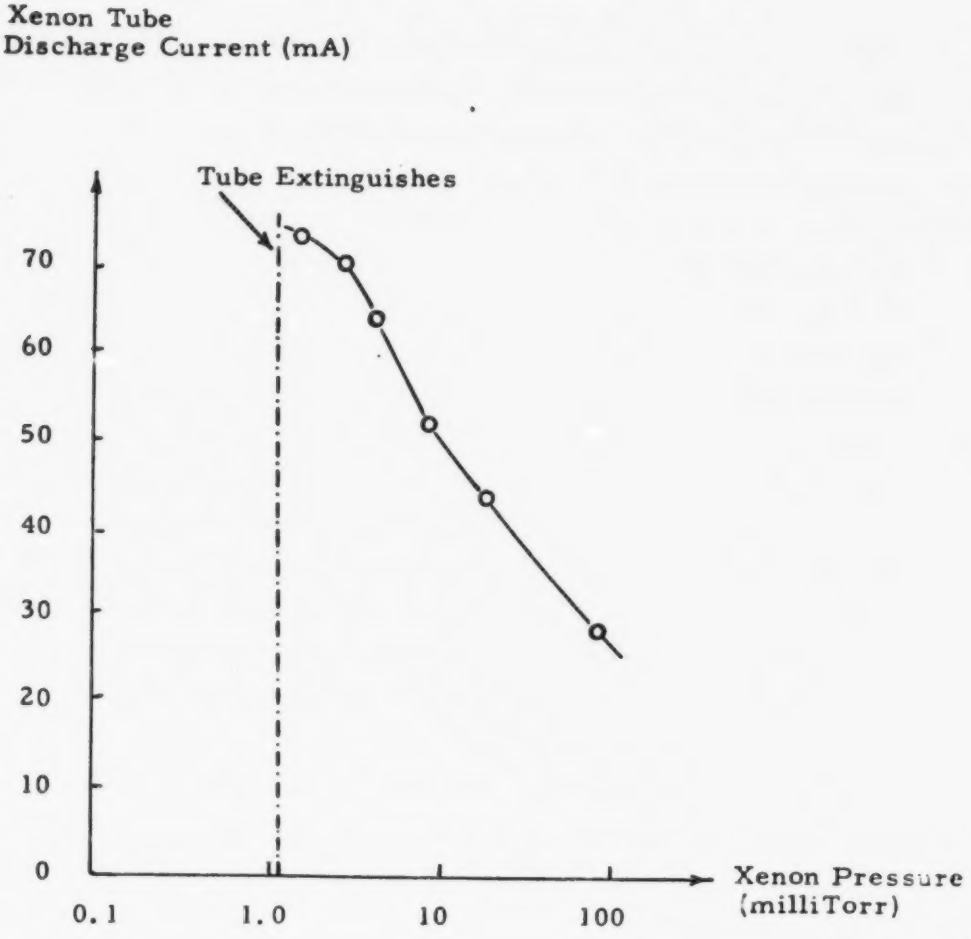

Figure 7-1 Pressure Dependence of Xenon Laser Discharge Current

pressure of several hundred milliTorr permits a discharge current of only 30 mA at the same anode voltage/load resistor combination.

Although each line exhibits a unique xenon pressure/discharge current set of operational curves, Figure 7-2 illustrates a typical example of a high-gain xenon laser line. In this case, the most important wavelength for the purposes of the aldehyde measurements, namely the 3.51 micron xenon laser line, is selected as the example depicted in Figure 7-2. As indicated in Figure 7-2, when the xenon pressure is too high, increases in discharge current reduce the output power of the laser rather than increase it. Under certain conditions of pressure and discharge current, some of the xenon laser lines will cease oscillation due to excessive pressure and discharge current. Those laser lines listed in Table 2-1 as requiring "low" xenon pressures will not oscillate at moderate xenon pressures. And, in general, those xenon laser lines requiring moderate xenon pressure will not oscillate at "low" xenon pressure.

In practice it will probably be necessary to use an external spectrometer of sufficient spectral resolution to separate clearly the relatively closely-spaced xenon laser lines; that is, if the individual optimization of each laser line is to be observed directly. Use of such a spectrometer is also advised, as mentioned in the following section, in the individual alignment of each laser line.

It is a good procedure to use the smallest discharge current which will produce an adequate output power from the LEM laser. In addition, higher pressure operation of the discharge tube tends to reduce the amount of cathode bombardment from heavy positive ions in the discharge. As mentioned in section 6.2, above, it is important to avoid operating situations in which the hot cathode is enveloped by the xenon discharge since such a situation is indicative of cathode bombardment (and consequently short life for the laser tube).

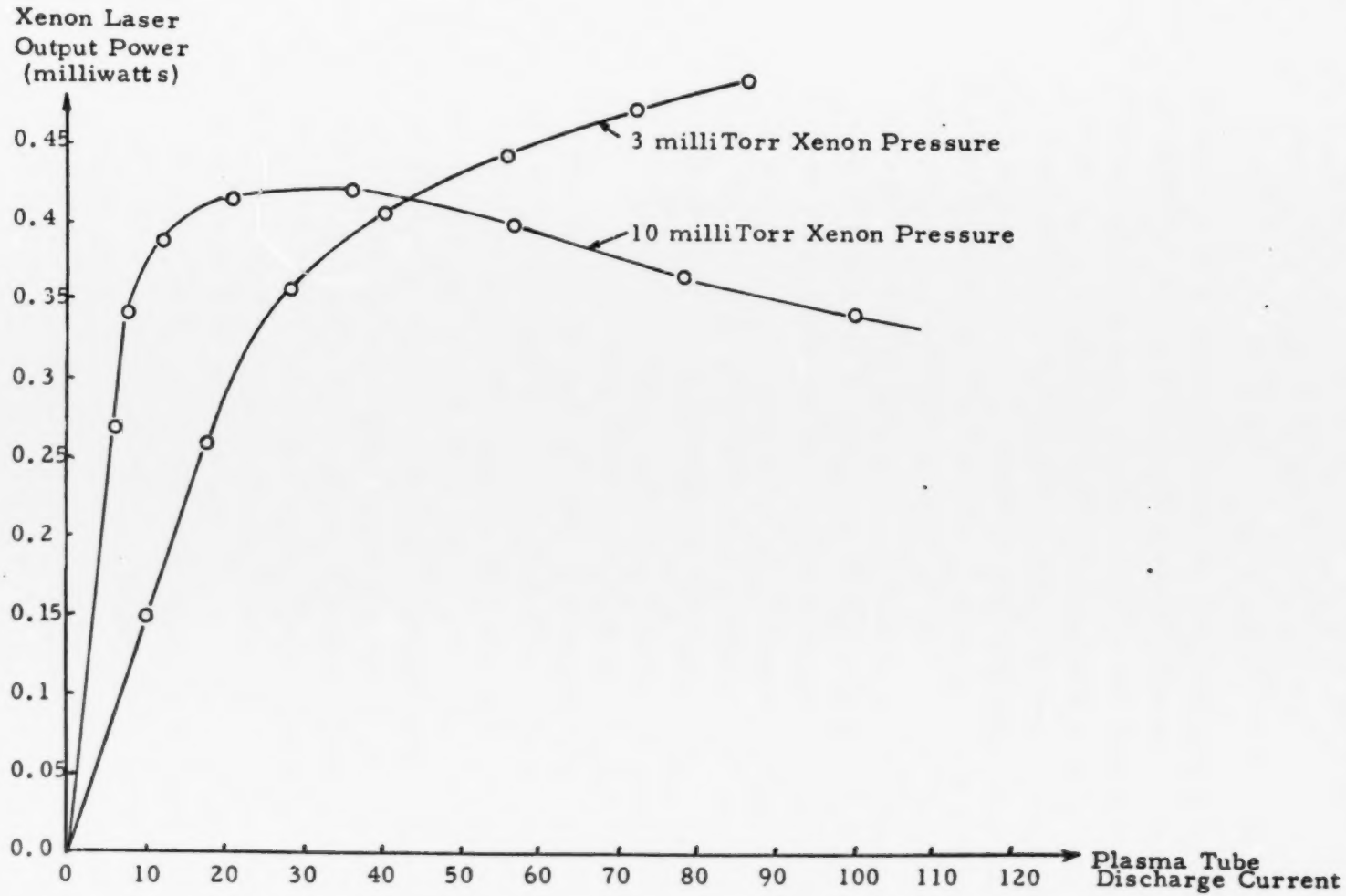

Figure 7-2 Xenon Output Power at 3.51 microns vs. Discharge Current

7.3 Laser Cavity Properties and Alignment Techniques

There are two types of laser mirrors furnished with the LEM laser. They are:

1. A plane-parallel Fabry-Perot cavity producing a well-collimated output beam, and
2. an afocal cavity producing a slightly converging optical beam.

Although the Fabry-Perot cavity mirrors produce a better collimated output beam than the afocal cavity mirrors, the afocal mirrors are considerably less susceptible to alignment variations produced by mechanical vibration or poor mirror adjustment. Thus the afocal laser cavity mirrors can be used to reduce the objectionable effects of the magnet cooling water pump vibration. This vibration source may not be a problem if the water pump is not used at the EPA, and the source of cooling water is tap water at an adequate pressure and flow rate.

Depending upon the particular needs of the experiment to be performed with the LEM apparatus, the Fabry-Perot or afocal laser cavity should be selected before the laser cavity alignment procedure is begun. The Fabry-Perot uses a plane high-reflectivity mirror mounted on the piezo-electric mirror translator while the afocal cavity uses a spherical mirror having a radius of curvature of 10 meters. The location of the piezoelectric translator is shown above in Figure 2-1.

7.3.1 Laser Cavity Alignment Procedure

Although it is possible to align a superradiant xenon laser using only the superfluorescent output from the laser, it is generally easier to use a small laboratory He/Ne laser oscillating at 0.633 microns to complete this task. The output beam from such an alignment laser should be directed parallel to and down the axis of the LEM xenon laser, with particular care being taken to center the alignment beam in the center of both LEM xenon laser tube windows. It will be useful to remove all of the LEM optical components from the optical bench to eliminate

dispersive optical wedges and opaque filters. Once the axis of the LEM laser tube has been defined, the output mirror can be installed in its collet with the dielectric coating toward the xenon laser tube. The reflection from the dielectric-coated surface of this mirror should then be brought into coincidence with the alignment laser beam. After this has been accomplished, the reflection from the high-reflectivity mirror should also be brought into coincidence with the alignment laser beam. It is often a considerable convenience to insert a beamsplitter into the alignment laser beam directly in from of the alignment laser in order to determine as accurately as possible the angular displacement of any reflected rays.

When both laser cavity mirrors are properly aligned, the procedure for starting the xenon laser (section 6.1) should be followed carefully, and the LEM photodetector assembly positioned in such a location that it will be able to intercept the entire xenon laser beam. This may require a degree of searching for the output beam, although the alignment laser often provides a relatively accurate reference to the direction and location of the output xenon laser beam.

The output xenon laser beam should pass through the centers of all the LEM optical component apertures without vignetting. The LEM optical component arrangement depicted in Figure 2-1 is recommended when formaldehyde absorption measurements using the furnished Nielson sample cell are desired. If a long optical path length White cell is substituted for the LEM aldehyde sample cell, the output beam divergence of the xenon laser (in the afocal case) may present a problem. The focal length of the spherical mirror used in this case is nominally 5 meters, and the optical power of this mirror can be corrected by introducing a negative lens of suitable optical power into the output xenon beam.

The final step in the mirror alignment procedure is to peak the fine laser cavity mirror alignment using the magnitude of the output signal from the LEM photodetector as a guide. As mentioned above

in section 7.2, a spectrometer can be used to complete the mirror alignment for the relatively weak, low optical gain xenon laser lines listed above in Table 2-1. Whereas the high-gain xenon laser lines (such as the 3.37, 3.51, and 5.57 micron transitions) are relatively easy to use in obtaining an approximate cavity mirror alignment, the relative insensitivity of these lines to cavity losses induced by poor mirror alignment makes it quite difficult to obtain excellent mirror alignment when the experimenter monitors the output powers of these lines only. Thus, when the relatively low-gain transitions (such as the 3.62 and the 3.86 micron lines) are used for the "touch-up" operation of the mirror alignment procedure, it is a relatively simple matter to obtain optimum cavity alignment.

For the purposes of performing absorption measurements on formaldehyde using the 3.51 micron xenon laser line, it may be advisable not to have the lower-gain xenon laser lines oscillating strongly. The 3.51 micron interference filter passes a small percentage of the xenon laser lines at 3.37, 3.62, and 3.68 microns, and if these lines are permitted to oscillate strongly, there may be an undesirable contribution to the detected signal. When the strong axial magnetic field is applied to the LEM xenon laser, however, only the 3.37 micron line will be able to partially penetrate the narrow-band 3.51 micron interference filter (the other laser lines fall below oscillation threshold in a strong magnetic field). The 3.37 micron laser line splits into two components also in a strong field, and it exhibits optical gain characteristics nearly as great as the 3.51 xenon laser line. As a consequence, it may not be possible to entirely remove the 3.37 micron laser radiation from the detected signal. This should not represent a serious problem to proper LEM system operation, particularly since such added signals can be compensated at either the dc reference amplifier or at the ac lock-in amplifier (see section 6.3, above).

7.3.2 Future LEM Laser Cavity Options

The utility of the stable CW xenon laser capable of laser oscillation at 11 wavelengths in the important infrared band from 3.1 to 5.6 microns

is not well exploited in the present LEM laser design. There are several additional laser cavity options which can permit additional flexibility in the operation of the LEM apparatus. Some of these are:

1. Additional output mirrors optimized for specific spectral regions: 3.1, 4.0, 5.7 microns, etc.
2. Additional (unpolarized) CW xenon laser tubes optimized for individual spectral regions: 2.0, 3.1, 3.5, 3.9, 4.5, 5.5, 7.0, 9.0, etc.
3. Broad-band Brewster's angle-equipped xenon laser tubes for use without a Zeeman-splitting magnet.
4. Introduction of a cavity Littrow prism to permit single wavelength laser oscillation.
5. Replacement of the present 1/4 wave plates with an adjustable electro-optical waveplate for use at a number of selected high-gain wavelengths using the Zeeman magnet.
6. An option in which two different xenon laser wavelengths are used to permit differential absorption measurements to be made in the absence of a magnetic field. In this option, one of the laser lines would be selected to avoid an absorption line, while the other would be centered as closely as possible on an absorption line. The unabsorbed line would then function as a reference in a differential absorption measurement apparatus.
7. Modification of the present LEM magnet to permit the use of large pulsed magnetic fields in order to achieve greater Zeeman splitting.
8. Introduction of pulsed noble gas lasers designed to oscillate at some 50 infrared wavelengths (from 1.2 to 9.0 microns).
9. Use of both a pulsed Zeeman magnet and a pulsed laser designed for extended tunable spectral performance.

In addition to the above, there are additional ways in which the signal to noise (S/N) ratio of the electronic data-processing equipment can be improved. Further details concerning any and all of these modifications can be obtained from the Laser Division, Hughes Aircraft Co., Culver City, California.

7.4 Coincidence of CW Xenon Laser Lines with Formaldehyde Absorption Lines

Following the data of Nielson (5), Table 7-1 lists the most obvious coincidences between five of the eleven CW xenon laser lines listed above in Table 2-1 and various P and R-branch absorption peaks in the infrared spectrum of formaldehyde.

TABLE 7-1

CW Xenon Laser Lines Near Formaldehyde Absorption Bands

#	Laser Wavelength (air)	HCHO Wavelength	$\Delta\lambda$	Line Identification
1	3.3667	3.3679	-12 Å	-2
2	3.5070	3.5100	-30 Å	6
3	3.6209	3.6206	+ 3 Å	-8
4	3.6507	3.6512	-5 Å	-19
5	5.574	5.577	-30 Å	22

Since there are six other CW xenon laser lines (several of which are quite strong) obtainable with the LEM xenon laser, it may be worthwhile to consider using dual or multiple wavelength absorption spectroscopic techniques to measure the relative concentrations of HCHO in the LEM sample cell (or an ancillary White Cell). Such dual (or multiple) wavelength absorption techniques could be employed without requiring the use of the large Zeeman magnet, albeit at the cost of sacrificing the 7 Å tunability of the 3.37 and 3.51 micron xenon laser lines. The differential absorption measurements could be made in a fashion quite similar to the present LEM techniques; namely, an unabsorbed laser line (such as the 3.27 micron line) is alternatively compared with an absorbed line (such as the 3.37 micron line), and the electronic data-processing circuitry compares the relative intensities of the two lines. The present LEM lock-in amplifier,

display, and recording electronics can readily be adapted to be used in differential absorption measurements of this type, and only the totating prism/analyzer assembly should require extensive modification (or replacement). A phase-locked scanning diffraction grating either in or out of the laser cavity can perform the function of synchronous, phase-locked wavelength selection/alternation for this application.

As discussed in the previous section, a xenon laser oscillator equipped with spectrally broad-band windows (such as Brewster 's Angle CaF_2 flats) is capable of CW or pulsed laser oscillation at infrared wavelengths in addition to the eleven laser lines listed above in Table 2-1. Such a laser would tend to emit linearly polarized light, however, and thus would not be entirely suitable for axial field Zeeman tuning.

8.0 LEM ASSEMBLY INSTRUCTIONS

The majority of the LEM components will be shipped completely assembled. Only the xenon laser and its associated hardware need extensive assembly, and an effort is made to simplify the assembly procedure as much as possible. Each laser cavity component is numbered and marked for proper orientation. This is also the case for the LEM wiring connections. It is only necessary to match the corresponding letters on the incoming leads with the letters on the terminal strips.

Upon receipt of the LEM equipment, each LEM system component should be carefully inspected for damage incurred during shipment. The laboratory site(s) and locations of the magnet power supply, Zeeman solenoid (to be mounted on the LEM optical bench), optical bench, electronic equipment rack, magnet cooling water pump, and magnet remote control should be selected and the proper power and water connections made. Both the high-pressure water pump and magnet power supply produce a relatively high level of noise when in operation, and it is recommended that the magnet power supply be located in an adjacent laboratory room if possible. Placement of the magnet power supply outside the laboratory in exposed condition is not recommended since it is important that the magnet power supply not be exposed to moisture since the large cooling fans would tend to draw moisture onto the high-voltage rectifiers.

Both a source and a sink of cooling water must be provided if a closed-cycle heat exchanger is not used with the LEM magnet. If the cooling water is to be dumped without recirculation, the 400 psi water pump can be used as a booster pump if a water source of from 3--4 gpm is available.

The magnet power supply is so large and heavy that a fork lift is needed to move it, and it is recommended that the site for the magnet power supply be completely prepared in advance of the delivery of the LEM system. At Hughes, the 3 Ø 480 V input is directed down from the laboratory ceiling through the top of the

power supply cabinet. The dimensions of the power supply cabinet are 46" (D) x 34" (W) x 63" (H), while those of the cooling water pump are 24" (W) x 24" (H) x 48" (L). The water pump also requires 3 Ø 480 V as a power source.

The Zeeman solenoid weighs approximately 300 lb., and may either be raised into place on the optical bench using a portable hoist, or if sufficiently burly technicians are available, four strong men can lift the solenoid onto the optical bench. As noted below, it is very important that the special optical bench foot be properly installed on the optical bench before the Zeeman magnet is put on the bench.

8.1 Assembly of the LEM Xenon Laser Cavity

All the LEM optical equipment is designed to fit on a furnished Ealing optical bench. For additional stability of the optical bench, an ancillary optical bench foot is furnished complete with adjustment screws. Matching protective metal plates should be placed under these adjustment screws to avoid marring the laboratory table top. This foot should be mounted on the optical bench FIRST before any other assembly is attempted. DO NOT place the magnet solenoid on the optical bench without this foot being in place since the torque exerted on the optical bench (in the absence of the extra foot) by the water-cooling manifold can cause the entire assembly to tip.

As shown above in Figure 2-1, the xenon laser cavity is constructed around the large Zeeman magnet solenoid, and hence the first step in the assembly of the xenon laser cavity is to locate the solenoid at one end of the optical bench. The solenoid mount should be flush with the end of the optical bench as shown below in Figure 8-1. As indicated, the centimeter scale on the optical bench should be on the opposite side of the solenoid coil from the water-cooling manifold. After this is accomplished, the following assembly procedure should be followed:

1. Attach the laser output mirror assembly, part #30, (using 1/4 20 Allen cap screws) to the inboard side of the Zeeman solenoid

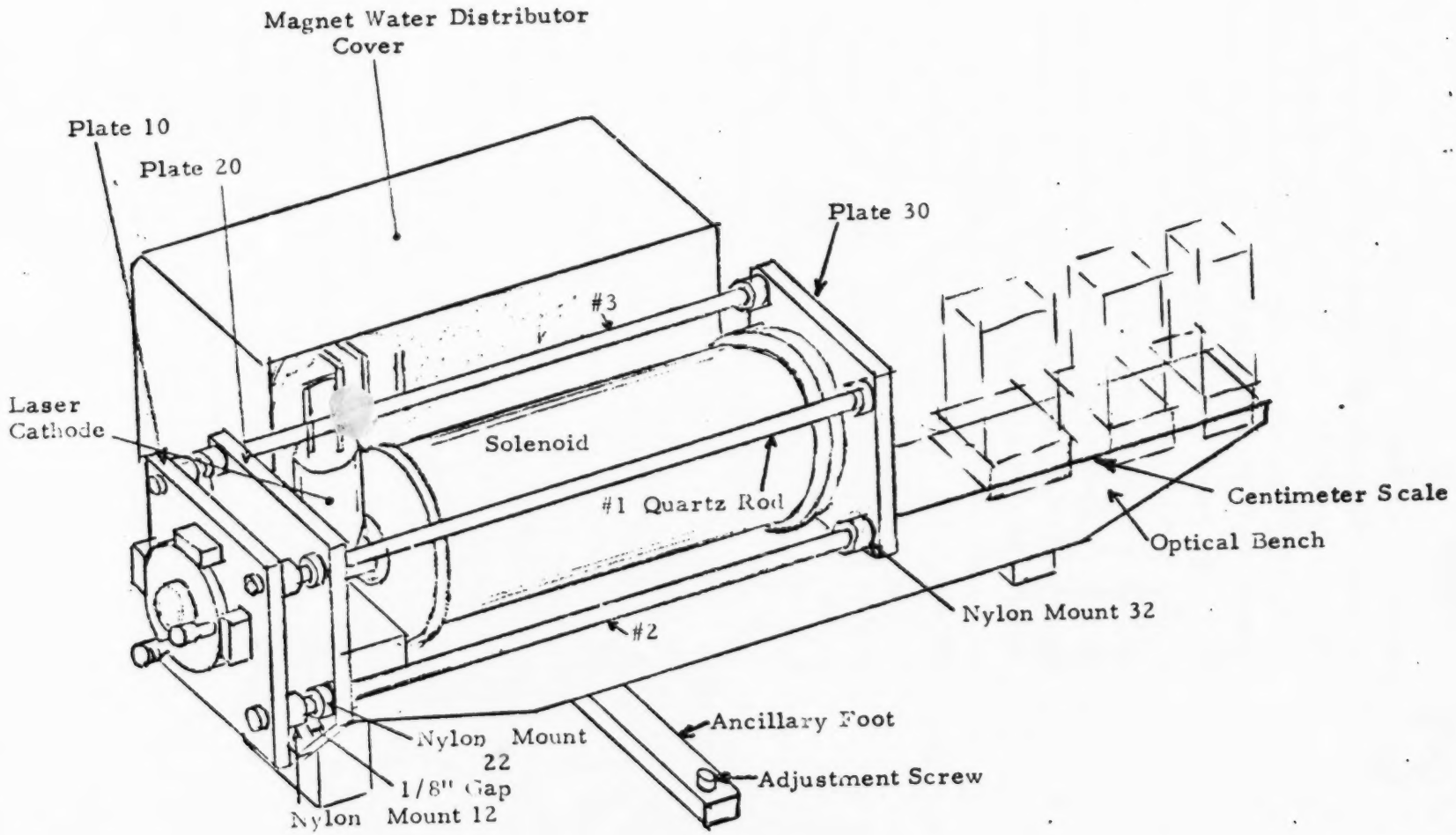

Figure 8-1 LEM Assembly Schematic

as shown in Figure 2-1 and Figure 8-1.

2. Insert the xenon laser discharge tube into the Zeeman magnet solenoid with the anode lead and trigger wire deployed along the solenoid axis. Observe Figure 2-1 for proper orientation of the xenon laser. Loosely clamp the xenon tube in the nylon mounting bracket on plate #30.

3. In a similar way, attach the quartz rod mounting plate, part #20, using spacers #25 and #26. Be certain that the xenon tube clamp is loose before attaching plate #20, and loosely clamp the xenon laser tube after the plate is properly mounted with the long 1/4 20 Allen cap screws.

4. Mount the xenon pressure-control dewar, part #27, between the solenoid mount and the quartz rod mounting plate, #20.

5. Insert the quartz stabilization rods, #1, #2, #3, and #4 in their respective apertures in plates #20 and #30; namely, rod #1 goes through aperture #31 in plate #30 and through hole #21 in plate #20. Rod #2 goes through aperture #32 in plate #30 and through aperture #22 in plate #20, etc.

6. Insert nylon mounts #31 (for aperture #31 in plate #30), #21 (for aperture #21 on plate #20), and #11 (for aperture #11 on plate #10) on quartz compensation rod #1. The corresponding nylon mounts should be placed on rods #2, #3, and #4. It is important to be careful while inserting the quartz rods into their respective mounts to avoid breaking these brittle rods. The nylon mounts must be oriented as shown in Figure 8-1.

7. Center the xenon laser discharge tube carefully along the axis of the Zeeman solenoid. Tighten the xenon laser clamp screws to hold the laser tube firmly, but not tightly.

8. Carefully mount the piezoelectric mirror assembly (part #10) to the quartet of quartz rods. Great care must be exercised in order to avoid breaking the quartz rods. A gap of approximately 1/8" should be left between mounts #11 & #21; #12 & #22, #13 & #23, and #14 & #24. After this is accomplished, the locking screws on these mounts should be carefully tightened.

The laser cavity mirrors can be inserted in their respective mounts and installed in the micrometer-adjusted collets. As indicated above in Figure 2-1, the high-reflectivity (spherical mirror in the afocal cavity case) mirror is installed in the piezoelectric translator head while the output (dielectric-coated) mirror is installed in one of the two smaller mirror mounts.

This completes the initial assembly of the LEM laser cavity. Optical alignment of the laser cavity can be accomplished by following the procedure outlined above in section 7.3.1. It is important to be certain that the xenon laser tube is rather accurately centered in the Zeeman solenoid to permit the laser beam to pass unvignetted through all the optical apertures in the LEM optical train.

8.2 Initial Assembly of Zeeman Magnet

The installation of the LEM Zeeman solenoid was described in the previous section. After the assembly of the laser cavity has been completed (according to the above procedure), it is only necessary to install the magnet cover and wire the magnet according to the directions(presented below) to complete the assembly of the LEM magnet system. The magnet cover is attached with the furnished round-head machine screws and washers. The cooling system assembly should follow closely the procedure outlined above in section 3.1 and Figure 3-3 to permit the magnet to be adequately cooled. The high-pressure hoses are characterized by having black cloth covers, and these high-pressure hoses are connected (as shown in Figure 3-3) to the magnet inlet water fitting and to the magnet water exhaust outlet. Relatively low water-pressure hoses are used for the remainder of the plumbing.

8.3 LEM Cable Connections

The initial set-up and wiring of the LEM apparatus is straightforward, and it requires relatively little time. It is VERY IMPORTANT, however, to insure that all wiring be doubly checked for accuracy BEFORE power is applied to any of the LEM circuits or components. The wiring of each major LEM subsystem is described below.

8.3.1 Wiring of Xenon Laser

The electrical controls of the LEM xenon laser are found in the upper portion of the electronic equipment rack. These controls are:

1. Laser cathode current (controls cathode temperature).
2. Dc Power Supply (discharge tube voltage and xenon laser discharge current).
3. Heater controls for cryogenic pressure-control system.
4. Laser tube starter.

In addition to the above controls, the analyzer prism motor, cooling fan, and sample cell heater are controlled from the LEM control panel. The interconnection of the cables from the LEM control panel to the individual LEM components constitutes the extent of wiring the xenon laser subassembly. Wherever possible, non-interchangeable connectors have been used to reduce the possibility of incorrect connections. The wiring procedure simply consists of matching the identifying letters on the LEM components with the corresponding letters on the cable leads coming from the LEM control panel.

8.3.2 Wiring of LEM Magnet

A similar procedure to that used in wiring the xenon laser subassembly is used for wiring the Zeeman magnet. The polarity of the heavy, high-current leads from the large magnet power supply must be carefully observed (see section 6.2.3, above, for information relating to the selection of current range of the magnet power supply). The LEM magnet control panel must have its two interlock and power cables correctly connected before it can be tested. As was the case with the xenon laser wiring, individual letters are used to identify and match these cables to their respective receptacles. Since the connectors are different, there is no chance of making an incorrect connection.

The large magnet power supply must be hard-wired to either a 240 V or 480 V 3 Ø 145 A (per phase) power source. It is strongly recommended that a semi-permanent site be selected for the magnet power supply before its delivery. As mentioned above, it is important

that the magnet power supply be located in a dry area not subject to adverse weather conditions.

The magnet cooling water pump also requires a 480 V 3 Ø source, but this unit can be soft-wired; i. e., it comes equipped with a standard 480 V 3 Ø connector at the end of a heavy cable.

8.3.3 Wiring of Electronic Data Processing System and LEM Equipment Rack

All of the LEM rack-mounted electronic devices derive their input power from the internal rack line cord (a circuit protected by a circuit breaker). The LEM dc amplifier obtains its dc supply voltages from the Keithley model 840 via a cable in the back of the equipment rack--the cable is marked with an identifying label.

The BNC and signal connections between and among the LEM prism analyzer, photodetector, and the Electronic Data-Processing System should carefully follow the schematic depicted above in Figure 4-1.

REFERENCES

1. A. Yariv, Quantum Electronics, John Wiley & Sons, N. Y. 1967.

2. C. K. N. Patel, "Gas Lasers" in Lasers, Vol. II, A. K. Levine editor, Marcel Dekker, Inc., N. Y. 1968.

3. B. A. Lengyel, Introduction to Laser Physics, John Wiley & Sons, N. Y., 1966.

4. A. Maitland and M. H. Dunn, Laser Physics, North Holland Publishing Co., Amsterdam, 1969.

5. H. A. Nielsen, Physical Review, 46, 117 (1934).

6. G. J. Linford, "High Gain Neutral Laser Lines in Pulsed Noble Gas Discharges," IEEE Journal of Quantum Electronics, QE-8, ,(1972).

7. S. C. Wang, et al., "Observation of an Enhanced Lamb Dip in a 3.51 Micron Xenon Laser," Applied Physics Letters, 17, 120 (1970).

8. R. Vetter, "Mesure des escarts isotopiques de 13 rais laser infrarouges dans le xenon," Compt. Rend. Acad. Sci., Series B, 265, 1414 (1967).

9. E. R. Peressini and G. J. Linford, "Effect of Cross-relaxation on the Spectral Flux and Population Inversion Distributions in a CW Laser Oscillator," IEEE Journal of Quantum Electronics, QE-4, 657 (1968).

10. G. J. Linford, unpublished xenon laser study, Hughes Aircraft Company, 1969.

11. W. R. Bennett Jr., "Gaseous Optical Masers," Applied Optics, Suppl. #1, 24, (1962).

12. A. Yariv, Quantum Electronics, John Wiley & Sons, Inc., N. Y. 1967, pp. 406-418.

13. G. J. Linford, "New Oscillation Dynamics of Noble Gas Lasers," University of Utah, Salt Lake City, Utah, Ph. D. Thesis, 1971.

14. G. Racah, Physical Review, 61, 537 (1942).

15. W. L. Faust & R. A. McFarlane, Journal of Applied Physics, 35, 2020, (1964).